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Impacts of implementing EU energy strategy – Baltic Sea region electricity market

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.
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Tiivistelmä

Diplomityön tavoitteena on on selvittää, millaisia vaikutuksia Euroopan Unionin energiastrategioilla on Itämeren alueen sähkömarkkinoilla. Tutkimuksessa tarkastellaan alueen hintoja, sähkön tuotantoa ja siirtolinjojen kapasiteetin riittävyyttän olettaen, että sähkömarkkinat kehittyvät EU:n tavoitteiden mukaisesti. Tarkastelu suoritetaan luomalla tulevaisuuden skenaarioita EU:n ilmasto- ja energiatavoitteita mukaillen. Skenaarioiden pohjalta luodaan simulaatiot, joiden avulla hinnat, sähkön tuotantomäärät eri tuotantometodeilla ja siirtokapasiteetit selvitetään.

Työ on rajattu Itämeren alueen day-ahead markkinaan. Rajauksen ulkopuolelle on siis jätetty päivän sisäinen sähkömarkkina ja säätösähkömarkkina. Itämeren alue sisältää Suomen, Ruotsin, Norjan, Tanskan, Viron, Latvian, Liettuan, Saksan ja Puolan. Työssä simuloidaan näiden alueiden sähkömarkkinaa vuosina 2015, 2020, 2030 ja 2050. Tutkimuksessa tarkastellaan kulutuksen sekä sähköntuotanto- ja siirtokapasiteettien muutoksia. Täten työn rajauksen ulkopuolelle jää sähkönsiirtotekniikoiden mahdollinen kehitys sekä erilaiset kulutusjoustomekanismit.

Katsaus EU:n energiastrategioihin osoittaa, että Euroopan sähkömarkkina on suurien muutosten edessä. Päästöjen leikkaaminen, tehokkuuden parantaminen ja yhteisen sähkömarkkinan rakentaminen asettaa suuria paineita kehittää markkinoita seuraavien vuosikymmenten aikana. Kehitys energiastrategioiden osoittamaan suuntaan on jo hyvässä vauhdissa, mutta suoritetut simulaatiot osoittavat, että haasteita on edessä. Skenaarioiden siirtokapasiteetteja tutkimalla havaitaan, että lisää siirtokapasiteettia tarvitaan erityisesti vuoden 2030 ja 2050 skenaarioissa. Ongelmakohdiksi paljastuu erityisesti Pohjois- ja Manner-Euroopan väliset siirtoyhteydet.

Uusiutuvien tuotantomuotojen, erityisesti aurinko- ja tuulivoiman, voimakas lisääminen päästötavoitteiden saavuttamiseksi aiheuttaa myös ongelmia sähkömarkkinoilla. Suuren tunneittain muuttuvan tuotantokapasiteetin johdosta siirtoverkko joutuu paineen alaiseksi. Siirtokapasiteetin rajoitukset aiheuttavat suuria hintaeroja ja sähkön hinta painuu negatiiviseksi erityisesti vuoden 2050 skenaarioissa.

Avainsanat sähkömarkkinat, energiastrategia, Euroopan unioni, siirtoverkot, energiaunioni, Pohjois-Eurooppa, markkinaintegraatio

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Abstract

The purpose of this thesis is to examine the effects of implementing energy strategies of the European Union on the Baltic Sea electricity market. This thesis investigates prices, production and transmission of electricity in the area assuming that electricity markets develop according to the EU strategies. The investigation is conducted by creating future scenarios that follow the development in the EU strategies. Based on these scenarios simulation cases were created. Simulations were run to find out prices, production amounts of different production methods and transmission capacities in each scenario.

The thesis is limited in the day-ahead market of the Baltic Sea region. The intraday and balancing markets are not considered in this study. The Baltic Sea region consists of Finland, Sweden, Norway, Denmark, Estonia, Latvia, Lithuania, Germany and Poland. In the thesis, the electricity market of this area is simulated in the years 2015, 2020, 2030 and 2050. This study focuses on describing the development of demand, production and transmission capacities. Demand flexibility mechanisms and possible development of transmission technologies are not considered in this thesis.

The review of the EU energy strategies reveals that European electricity market is facing great changes. Cutting emissions, improving efficiency and building a single electricity market sets huge pressure to develop the markets in the following decades. The development towards the path set by the energy strategies is already in good progress, but the simulations show that challenges are ahead. By investigating transmission capacities in the scenarios the inadequacys of the transmission grid are revealed. Problems arise especially in the 2030 and 2050 scenarios with transmission lines between the Continental Europe and the Nordics.

Reaching ambitious emission reduction targets force the member states to rapidly increase solar and wind production. The increase of variable renewables cause problems in the electricity markets. Having large hourly variating production capacity stresses the transmission grid. The increase in cheap variable production capacity added to inadequacies in the transmission capacity create price differences and even negative electricity prices especially in the 2050 scenarios.

Keywords electricity markets, energy strategy, European Union, transmission grid, energy union, Northern Europe, market integration

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Helsinki 27.5.2016

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Table of contents

1 Introduction 1
2 EU Energy strategies 3
2.1 Liberalization of the European electricity markets 3
2.2 Energy Union 4
2.2.1 Motives behind the Energy Union 4
2.2.2 Energy Union targets and implementation 6
2.3 Energy 2020, 2030 and 2050 10
2.3.1 Energy 2020 10
2.3.2 Energy 2030 12
2.3.3 Energy 2050 14
2.4 Summary of the EU Energy strategies 17
3 European electricity grid 19
3.1 European electricity grid today 19
3.2 Grid development 21
3.2.1 Making the grid smarter 22
3.2.2 ENTSO-E plans for grid development 26
3.3 Summary of the European electricity grid 31
4 The Baltic Sea region electricity market 33
4.1 Electricity markets and exchanges 33
4.2 Price calculation and formation 36
4.3 Situation in the Baltic Sea region countries 38
4.3.1 Norway 39
4.3.2 Sweden 39
4.3.3 Finland 40
4.3.4 Denmark 40
4.3.5 Estonia 40
4.3.6 Latvia 41
4.3.7 Lithuania 41
4.3.8 Poland 41
4.3.9 Germany 41
5 Market simulation 43
5.1 Simulation data 44
5.1.1 Demand 44
5.1.2 Production 45
5.1.3 Capacity factors 49
5.1.4 Pricing of production 51
5.1.5 Capacities and connections 53
5.2 Simulation process 54
6 Results and analysis 56
6.1 Generation 56
6.2 Prices 60
6.2.1 Finland 61
6.2.2 Poland 62
6.2.3 Germany 63
6.3 Electricity flows 64
6.4 Summary 66
7 Conclusions 68
Sources 72

List of abbreviations

CCS	Carbon capture and storage
CHP	Combined heat and power
EEGI	European Electricity Grid Initiative
EIA	United States Energy Information Association
ENTSO-E	European network of transmission system operators for electricity
ETS	Emissions trading system
EU	European Union
GHG	Greenhouse gas
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LNG	Liquified natural gas
NREL	National Renewable Energy Laboratories
NVE	Norwegian Water Resources and Energy Directorate
PCI	Project of common interest
RIP	Regional Investment Plan
TSO	Transmission system operator
TYDNP	Ten-year network development plan

1 Introduction

The European energy sector is going through drastic changes during the next few decades. New and rapidly developing technologies have enabled production of near zero-emission electricity while traditional methods of electricity production are sometimes even frowned upon. International agreements and changes in general opinion have pushed decision makers towards more environmentally friendly policies all over the world. In almost every developed, and also in some developing countries, the pressure to create cleaner and more efficient energy solutions is building up. In 2050 the energy sector has probably little resemblance to what it is today. The European Union and its member states have assumed the role of a pioneer in this energy revolution.

In addition to international agreements the EU has introduced many of its own policies, goals and roadmaps to push even harder to make its member states an example to the rest of the world. EU has different strategies for development of its energy sector in different time frames. The Energy 2020, 2030 and 2050 strategies form a roadmap towards EUs goals for energy sector. They include goals on energy security, sustainability of production methods and competitiveness of electricity prices. For these goals to become reality the EU plans on forming an Energy Union. An entity in which the energy is affordable, supply is secure and environmentally friendly. In the Energy Union the flow of energy is not restricted and it is considered as a "fifth freedom" for all EU citizens. Implementation of these strategies have undoubtedly a massive effect on the electricity markets, production volumes of different methods and electricity prices.

The goal of this thesis is to simulate how the EU energy strategy and realization of its goals affect electricity markets in the Baltic Sea area. This is done by studying different strategies and finding the key elements that they promote. Electricity production mixes, demand development and new interconnections as well as marginal prices and capacity rates of different production methods are forecasted in every country based on the EU strategies and earlier research. These figures are then transformed into scenarios. Using these a simulation is carried out to find out how these strategies affect in the Northern European electricity market in 2020, 2030 and 2050. Prices and usage of different production methods is analysed based on the simulation. Also effectiveness of the EU strategies will be evaluated based on the simulation results.

This thesis focuses on the Baltic Sea area which in this study means Nordic countries: Finland, Sweden, Norway and Denmark; and Baltic countries: Estonia, Latvia and Lithuania. In addition to this the main electricity interchange partners Germany and Poland are included. These countries are selected because of the large amount of existing electricity trading and co-operation as well as large amount of future plans to connect the markets in these countries. Excluding other countries such as the Netherlands and Russia reduces the accuracy of the simulation as changes in one part of the grid affects everywhere. However taking into account every EU country would make the scope of this thesis too wide. This study is also limited to day ahead market, so a part of the actual electricity trading in intraday markets and balancing markets as well as bilateral trading and financial markets are left out. All the produced electricity is considered to be traded in day ahead markets to simplify simulations.

The thesis consists of six main chapters. First chapter takes a closer look on the EU energy strategies for 2020, 2030 and 2050. Also EUs Energy Union plans are investigated more closely. In this chapter the main goals and plans to reach them are studied. The second chapter focuses on the European electricity grids as it it's one of the most important tools to reach EU goals and enable free flow of energy throughout the Energy Union. Situation of the grid today is studied to recognize weaknesses as well as plans for the future. The third chapter concentrates more on the electricity markets in the Baltic Sea area. What is the situation now and how it will develop in the future? How the market works and price is formed and calculated in European markets is also one of the focus points. In the fourth chapter the simulation is explained in detail. Different parameters and their basis for each scenario is presented and price calculation system and the whole process is explained. Finally the results are presented and analysed. The prices, generation of electricity and flows of power in the region are evaluated and possible weaknesses and challenges identified.

2 EU Energy strategies

This thesis relies strongly on different EU policies regarding future development of energy sector. These policies include different strategies for the future up until the year 2050. To be better able to understand and simulate different scenarios for the future, these strategies must be carefully studied as they form a basis for the simulations.

In the following chapters the key points in each strategy, 2020, 2030 and 2050 as well as Energy union policy are introduced. The three energy packages that have formed European energy market to what it is today are also presented. Finally all these strategies are summarized in order to form a clear path of European energy policies from this day to the year 2050.

2.1 Liberalization of the European electricity markets

The push towards the common European electricity market begun already in 1990s. The first steps to reach this goal was to liberate European electricity markets from unnecessary regulation and to enable competition. In 1996 the European Parliament agreed on the first liberalization package, directive 96/92/EC, which forced the member states to partially liberate their national markets. A liberalization of 25-33% of the market was required from each member state by the year 2003. The goal of this directive was not to just liberate the markets inside the isolated member states. This first step already had its goal in establishing a common electricity market that would consist the whole European Union. (Commission of the European communities 1999)

The second liberalization package was introduced in 2003. The new directive continued the progress started in the first liberalization package. This directive set the common rules for production and distribution of electricity by imposing rules that control for example access to the market and common procedures. The second liberalization package forced the member states to separate transmission system operation from distribution system operation. This means that same company can't be responsible for both of these activities. (2003/54/EC 2003)

This directive also made all non-household customers eligible. This means that these customers gained right to choose between suppliers freely. The directive stated that member states should also ensure the household customers to be supplied with electricity of a specified quality in their territory at reasonable and transparent prices. Also actions to ensure supply security for the customers were enforced. (2003/54/EC 2003)

The latest and most comprehensive package was given in 2007. It continued and expanded the actions in the previous two packages. To further open the electricity markets for competition, household customers were given the same right to choose between suppliers as the industrial customers had been given in the second package. The third package also forced further unbundling of ownership within the energy sector. Production and distribution actions were separated from each other. The purpose of this was to eliminate vertical integration, or one company owning the whole supply chain, which could lead to monopolization of the markets. (2009/72/EC 2009)

The National Regulational Agencies were established as a result of new directive. These agencies were created to have a single regulational authority in each member state. The responsibilities of the National Regulational Agencies include negotiating tariffs, co-operating in cross border transmission projects, monitoring the energy sector and reporting to European Union.

2.2 Energy Union

Forming an Energy Union was first proposed by former prime minister of Poland Donald Tusk in 2014. His main concern was, in the time of disputes between Russia and Ukraine, the energy security of the European Union. Many of the member states, especially in Eastern Europe are heavily dependent Russian gas. Tusk feared that Russia might use its monopolistic position in energy sector as a political weapon to react to surrounding political situations by raising prices or reducing supply. To counter Russia's strong influence in European energy sector Tusk proposes an Energy Union. In Tusk's proposal the main focus is on energy security and it is crystallized in five action points. (Tusk 2014)

First EU should negotiate its energy contracts jointly rather than separately in each country. This would make the EU a bigger entity and increase influence in the negotiations and ensure reasonable pricing. Member countries should also begin developing mechanisms to divide supplies in case of a supply cut off. Third, the EU should endorse investments in energy infrastructure to increase energy independency. Increasing co-operation with other external countries is also one of the main points. Developments in transportation and storing technologies have enabled efficient LNG transportations in addition to traditional pipelines. In addition to these Tusk wants EU to not hinder the usage of existing resources, such as coal, in the member states. (Tusk 2014)

2.2.1 Motives behind the Energy Union

The five initial action points have since evolved to the Energy Union. The scope of the Union has widened a lot from Tusks original idea. In addition to energy security, other issues have since been raised that could be solved with common management of energy affairs. One of these issues is the price of electricity. Both industrial and household customers in Europe pay in average more for their electricity than in other industrialized countries as can be seen from figures 1 and 2 below. (European Commission 2015a)

The high price of electricity weakens EU member states possibilities to compete against for example US, China and Korea in the global markets. Especially the electricity intensive industries are effected by the high prices. In these industries which include for example metal, paper and chemical industries the price of electricity forms a key competitive advantage. The EUs high prices makes it nearly impossible for EU based industrial manufacturing to compete in the global marketplace. (Fraunhofer ISI, ECOFYS 2015)

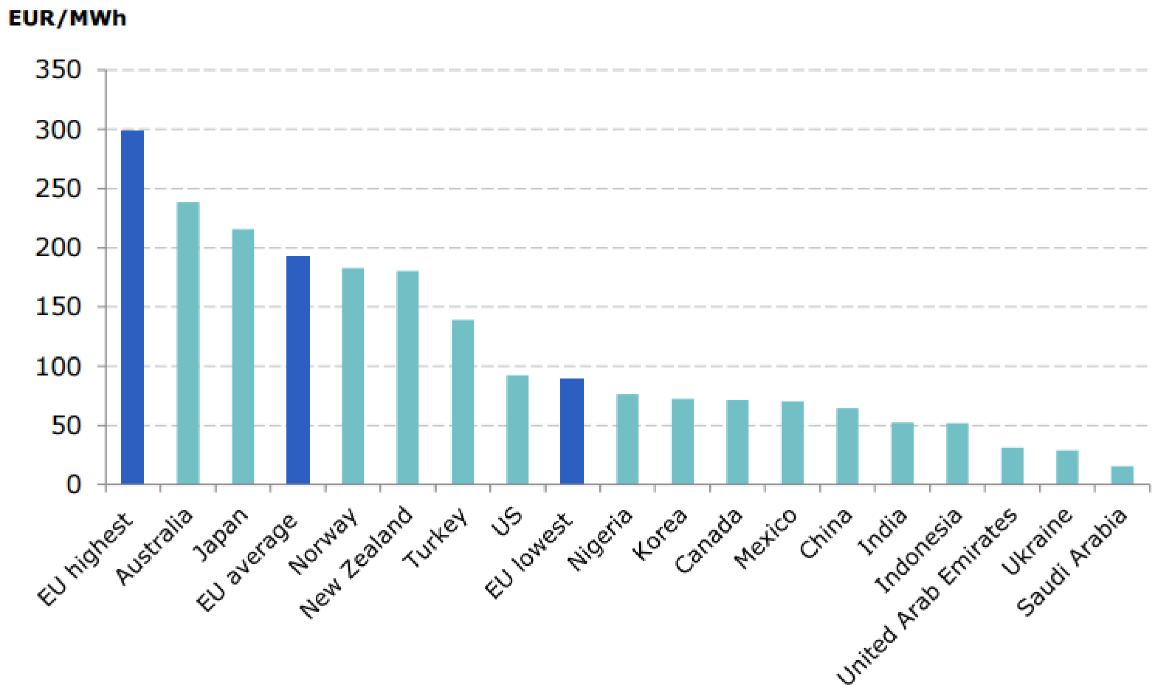


Figure 1. Price of electricity for household customers. (Juncker 2015)

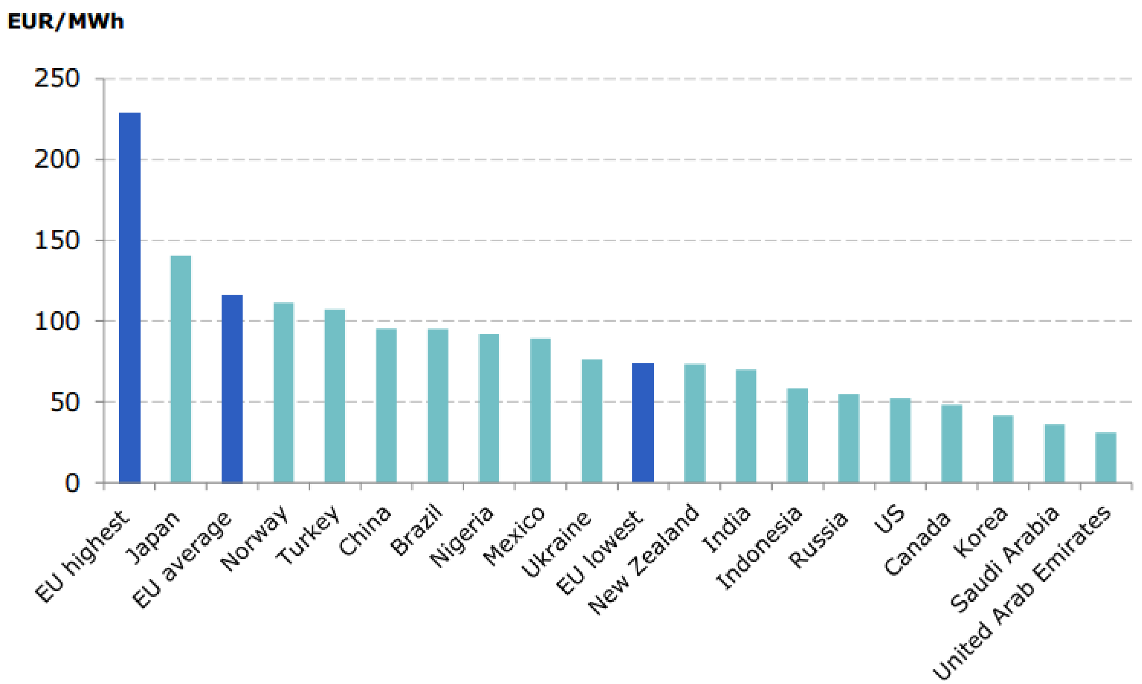


Figure 2. Price of electricity for industrial customers. (Juncker 2015)

Another issue regarding electricity prices is the large variation of the prices. Difference between the highest and the lowest price in EU area is about 200 €/MWh for household customers and 150 €/MWh for industrial customers. This is due to fragmented electricity markets.

Europe, though otherwise very connected, is still somewhat separated when it comes to energy markets. (European Commission 2015a) The inefficiency of cooperation and in-adequacy of physical connections between the member states create areas of exceptionally high and low prices of both electricity and gas. Evening out these inequalities in energy prices would make EU a stronger competitor in the global markets.

Reducing fragmentation in the European energy market would bring also other benefits. Increasing physical connections between and inside the member states would guarantee supply security to all customers. Having many possible suppliers reduces the possibility of total cut off. This would also give power to the customer to choose between suppliers from a larger geographical area. This would increase competition in EU internal markets and prevents unfair pricing. (European Commission 2015a) If the whole EU could be considered a single energy system by creating an efficient energy distribution grid, great savings could also be gained. The need for peak load power plants would be decreased and the existing power plants could be run in more efficient manner. (European Commission 2015b)

The EU is the biggest energy importer in the world with imports of today 53% of total consumption. The total cost of the imported energy is around 400 billion euros so urge to reduce import share is great. (European Commission 2015a) The EU aims to reach this reduction of import share by massive increase of renewable energy production. The EU Energy Roadmap high renewable energy scenario projects even 97% share of renewable energy in EU by the year 2050 (European Commission 2011a).

The renewable energy resources are domestic and in most of the regions adequate to meet consumption so they could easily reduce the amount of imported energy. While solar and wind energy have a great potential to meet the energy demand in the future, they lack dispatchability. The need for cooperation between member states and efficient transportation of energy becomes vital when share of renewable energy grows larger.

In addition to cheaper electricity prices, connection of markets and security of supply, there are also other issues that Energy Union is expected to answer. Separate member states have little influence in international energy politics. Advocating own national policies often leads to nowhere. Forming a single entity with common goals and policies can hoist EU to same level with other political giants like China, US, Russia. (European Commission 2015a) Making common decisions on energy policies would also be environmentally beneficial. Energy efficiency and climate regulations could more easily be enforced.

2.2.2 Energy Union targets and implementation

Energy Union seeks to tackle the above introduced problems by creating an energy system that is secure, competitive and sustainable. These three targets are the basis of all EU energy strategies. The Energy Union has created five dimensions on which the realization of the three targets rely. These are: Energy security, solidarity and trust; A fully integrated European energy market; Energy efficiency contributing to moderation of demand; Decarbonising the economy; Research, innovation and competitiveness. (European Commission 2015a)

First of the five dimensions, Energy security, solidarity and trust, relates closely to the target of secure energy system. Vulnerability of EU to external energy risks is worrying. Thus the need to increase independency and diversity of energy suppliers is great. Main method of increasing security is building an efficient internal energy market and more flexible and efficient consumption. Solidarity is called for between the member states to decrease the risk from external sources. (European Commission. 2015a)

Diversification of supply focuses mainly on natural gas supply because of the monopolistic status of the market today. As seen in figure 3, EU is highly dependent on major fuels. Supply diversity is going to be achieved by building new gas line, Southern Gas Corridor to allow EU to purchase gas from Central Asian countries.

Other methods include wider implementation of liquefied natural gas hubs that have been built in Northern Europe. (European Commission 2011b) These hubs do not rely on single supplier hence decreasing the dependency on any single supplier. They are also flexible to changing prices and allow price competition. LNG can also be stored which increases security in time of a crisis. Diversification of supply is also needed with other fuels. EU is still dependent on nuclear power so ensuring uranium supply is seen as a priority.

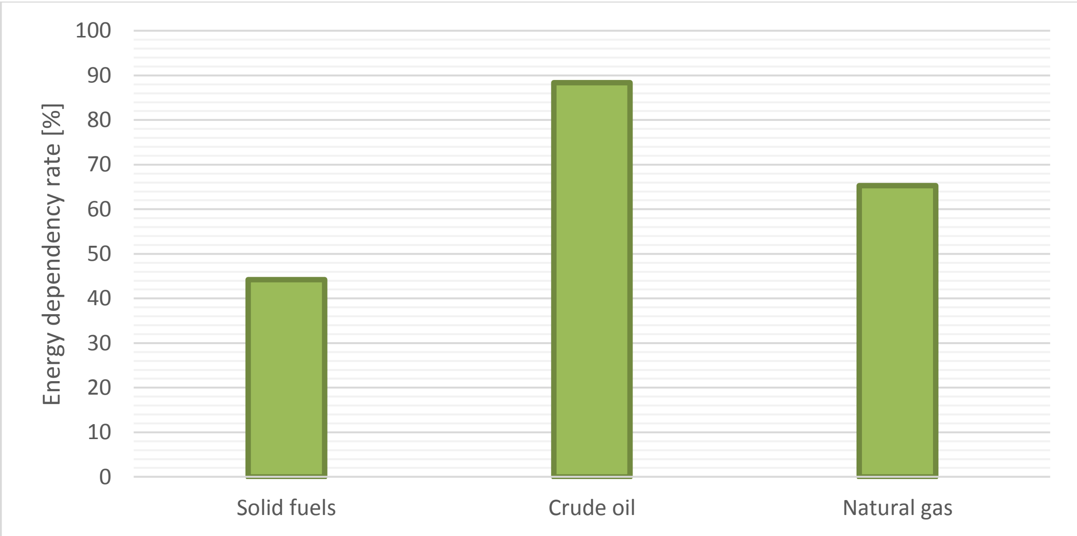


Figure 3: Energy dependency rate by fuel type EU-28 in 2013. (Eurostat 2013)

As important as it is to ensure the necessary fuels, the best way to increase energy security is to increase internal energy production. Member states do not possess large amounts of domestic fuels, apart from some coal and shale gas. (European Commission 2015a) Increasing production using conventional fossil fuels would not only decrease the energy independency but also increase emissions. Thus the EU emphasizes highly on increasing the renewable energy production. Another alternative to using coal and gas are biofuels such as wood, waste and biogas. These fuels are always domestic and can be utilized with similar technologies as conventional fossil fuels.

Cooperation between the member states is one important aspect in making EU more energy secure. Directives and plans have been set to make the EU countries work together for common energy security. An example of such enforcement of cooperation is the directive that obligates the member states to stock crude oil and other fuels (Council of the European Union 2009). Another example are the emergency plans have already been made. Cooperation between transmission system operators and other stakeholders in energy sector is going to be strengthened. (European Commission 2015a)

Working together makes EU more secure not only internally, but externally as well. By joining forces, the member states can challenge the energy superpowers in the world and gain leverage in for example natural gas trade negotiations. EU plans to make energy security a priority in its energy policy. It seeks to strengthen collaboration with strategic energy partners as well as look actively for new companionships to diversify energy supply. (Janka 2015)

The next dimension, a fully integrated European energy market, is a key to reaching all the three targets of Energy union. It enables the transfer of energy in the times of crisis, to increase competition and to deploy more renewables. The integrated electricity market is probably most important of the dimensions as failure in this would mean failure in all the other dimensions. Though the first steps are already taken towards internal energy market a new push must be made to complete it.

Building infrastructure to connect Europe as a single energy market is an ongoing project. Insufficiencies of especially the cross border connections of electricity and gas networks have been noted and several infrastructure projects have been commenced in the recent years. European network of transmission system operators for electricity (ENTSO-E) has identified almost 250 Projects of common interest (PCIs) which are vital for completing internal energy market. (ENTSO-E 2014) These projects are partly EU funded to accelerate their progress.

PCIs are mostly projects that increase connectivity between two countries. This is because EU has set specific minimum targets for interconnection rate. Target of 10 % interconnection has been set for 2020 and 15 % for 2030. By completing PCIs in given timeframe, these targets will be met. (European commission 2015b) PCIs and physical development of the European electricity grid is investigated more elaborately in chapter three of this thesis.

Implementing internal electricity market requires more than physical connectors. Enforcing existing plans and legislation relating to increasing competition and removing barriers between areas is vital. Effective regulatory framework is needed to build an energy market consisting whole EU. Cooperation between transmission system operators is to be increased and more influence is to be issued to Agency for Cooperation of Energy Regulators to ease the cross border decision making. Also legislation to redesign whole electricity market is currently planned. With this EU wishes to link wholesale and retail of electricity. This would increase adaptivity to multitude of renewable suppliers and make the market more demand flexible. (European commission 2015a)

Improvements in third dimension, Energy efficiency as a contribution to the moderation of energy demand, makes EU more competitive and sustainable. EU energy efficiency improvement target of 27% by 2030. As can be seen from figure 4 below, households and transport add up to almost 60% of all consumption in Europe. The main focus of efficiency efforts focuses on these two sectors. Major investments are needed to improve efficiency of heating and cooling buildings. Also legislation of building requirements is going to be improved to ensure the usage of more energy efficient materials and heating and cooling methods. Transport is not only major energy consumer but also a major source of emissions. In addition to road charging and improvements on public transport to reduce private motoring, EU tries to promote electrification of transport.

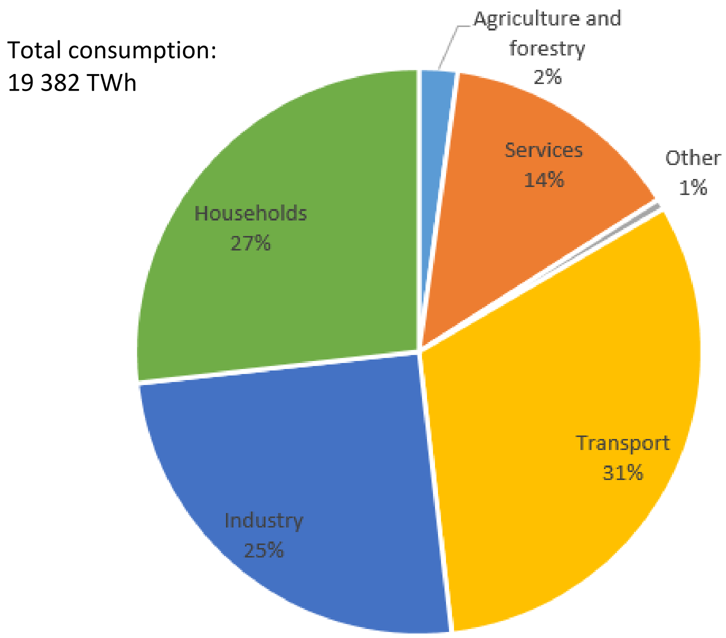


Figure 4: Final energy consumption EU-28 in 2013. (Source: Eurostat 2013)

In addition to electrification of transport, the fourth dimension, decarbonising the economy, is going to be achieved by efficient emissions trading. Increasing the cost of greenhouse gas emissions to a level that pushes towards cleaner production methods will be a cornerstone in the EU climate strategy. Improvements in emissions trading is going to provide cost-efficient and impartial way to reduce emissions throughout the EU.

The EU wants to push its member states to become number one in renewable solutions in the world. This requires both utilizing existing and developing new technologies. Aggressive scenarios and plans predict renewable capacity share rise to a level of 90 % by year 2050. (European Commission. 2011a). The official target for 2020 of 20% of renewable energy share in production is most probably going to be met. The next target is 27% of renewables in 2030. (European Commission. 2015a) This target is a bit more challenging. It requires successes in other dimensions such as integrating markets, for a share that big could result to instability of the electricity network. EU plans to support growth of renewable supply but tries to avoid it resulting market distortion. Resource availability, public acceptance and local grid must be taken into account when planning new renewable production (European Commission 2013a).

The fifth and final dimension of the Energy Union is research, innovation and competitiveness. This dimension aims to all three targets of the Energy Union. If the EU is going to be number one in renewables and rise to same league with other big players of the energy sector, the EU also needs to be on the top when it comes to coming up with new solutions. Making energy reform towards carbon free production requires massive leaps in technology. Storing of electricity and smart grid technologies are not yet developed enough to allow high amounts of renewable production. The EU plans to boost research and innovation efforts by combining different programs and focusing research more to the most important issues. Strengthening of the research and innovation effort can bring new jobs and opportunities for economic growth in the EU. (European Commission 2015a)

These five dimensions crystallize the plans for achieving Energy Unions three targets: secure, competitive and sustainable energy system. They are aimed to alleviate or remove altogether problems that hinder the development of Energy Union. Succeeding in these five dimensions will make the energy reform, that the Energy Union promotes, a reality.

2.3 Energy 2020, 2030 and 2050

The European energy sector will through major changes in the following decades. The EU has divided the planning and monitoring of the progress according to different time steps, 2020, 2030 and 2050. Individual targets have been for the each point in time. This study investigates measures to develop energy sector in Europe according to 2020, 2030 and 2050 strategies. That is why it is important to understand what the EU plans are. These plans, their targets and ways of reaching them are described more in detail in the following chapters. Also progress of the plans and fulfilment of the targets is evaluated. The most important aspects regarding to this study are summarized.

2.3.1 Energy 2020

The 2020 climate and energy package predates the birth of the Energy Union. The Europe 2020 Strategy including climate and energy package was introduced in 2007. At the time the European Commission estimated that over 1 trillion euros is going to be invested to improve infrastructure of the European energy system over the following ten years.

These infrastructure investments will affect European energy system for decades to come, so framework to steer the investments is required. The main goals of this package, also known as 20-20-20 strategy, are the following: 20% reduction of greenhouse gas emissions, 20% improvement in energy efficiency and increasing the renewable share to 20%. These goals are to be reached by 2020. Since the introduction of the Energy Union, these plans have been integrated as a part of it. (European Commission 2012)

Emission reduction targets of 20% are going to be reached mainly by using two tools. First by legally forcing the member states to reduce their emissions. Each country has a national reduction target which varies between the member states. The national target is set based on the member states wealth. The targets vary between reductions of 20% in the wealthiest counties and limiting the increase of GHGs to 20% in the least wealthy countries. These national reduction or limitation targets cover about 55% of all emissions. The targets cover for example transportation, housing and agriculture. (European commission 2013b)

The rest, about 45% of the GHG emissions are covered by emissions trading system (ETS). The ETS covers emissions that can be measured accurately. This means for example power plants, energy intensive industry such as metal industry and commercial air transportation. Participation is mandatory for companies covered by emissions trading system. The EU ETS works on the "cap and trade" principle. A "cap" or limit is set for volume of GHGs emitted by the covered companies. The companies can then buy permission to emit GHGs for a certain price. These permissions can also be traded between the companies. (European commission 2013b)

The EU ETS has gone through two phases before it has reached its current state. The first phase from 2005 to 2007 was a pilot period to set up the system. The first phase succeeded in establishing a market for carbon emissions and helped to set up monitoring and reporting of the emissions. A penalty for not reaching the limits was set to 40€/t(CO_2). Phase two from 2008 to 2012 introduced more countries to ETS and also included nitrous oxide emissions to the system. In both of these phases almost all of the emission permits were given to companies for free so the system was not really efficient in reducing emissions. The caps were also not EU wide. The third and current phase from 2013 onwards works by auctioning the permits instead of giving them for free. The EU wide emission limit is also set and reduced by almost 1.74% yearly. The EU ETS is forcing electricity producers to shift to emission less production and thus commit in increasing the renewable share. (European Commission 2012)

Reaching the 20% energy efficiency targets are monitored on EU level. Each country is required to set their own indicative targets for energy efficiency which should combined add up to 20% on EU level. The efficiency improvements are based on energy consumption, energy savings or energy intensity depending on each country preferences. Energy efficiency efforts are mainly focused on housing by renovations and improving the efficiency of appliances and transportation. In industry, the energy efficiency improvement targets are going to be reached by better equipment and machines. More careful energy planning is also encouraged and information provided to help save energy throughout the supply chain. (2012/27/EU 2012)

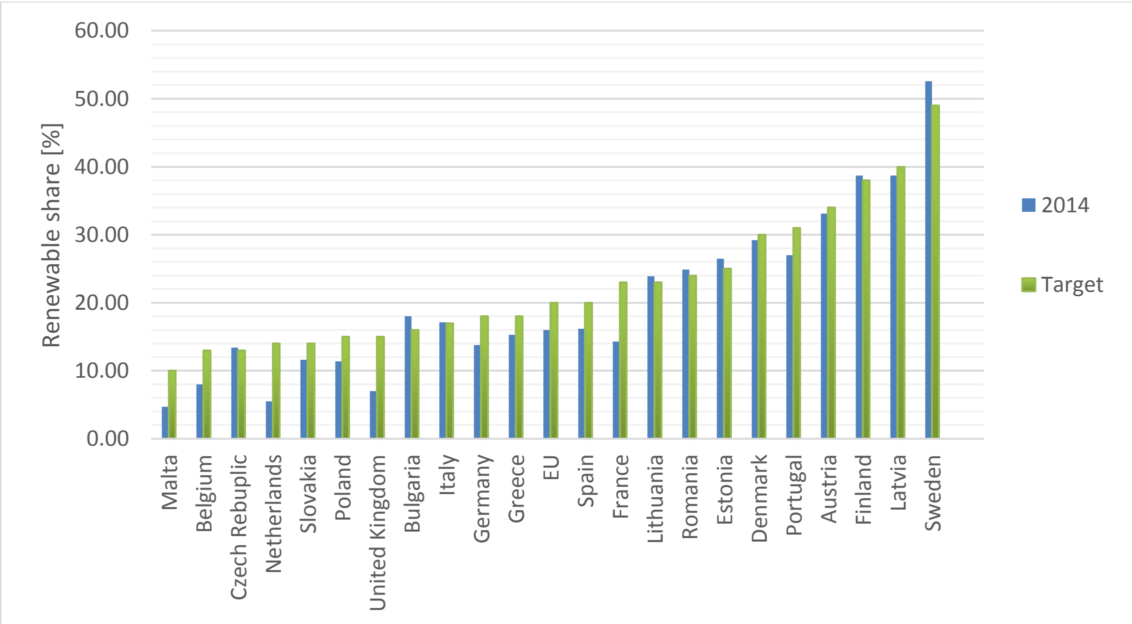


Figure 5: Renewable share targets and progress in 2014. (Eurostat 2014)

The third main target of the Energy 2020 strategy is to increase the renewable share in consumption by 20%. This is more than double the 2010 renewable share, which was 9.8%. In addition to 20% renewable share, the EU is going to raise the share of renewables in transportation sector to 10%. Once the individual member states have unique targets of their own. These can be seen from figure 5 below. The renewable share target has also the largest variance between the individual targets. Country specific renewable share targets vary from 10% in Malta to 49% in Sweden (Eurostat 2014).

Overall these targets add up to EU target of 20%. These numbers reflect the initial situation in each country before introduction of the Energy 2020 strategy. This means basically the amount of existing renewable production capacity but also availability of renewable resources. The member states have introduced plans to meet the targets in national action plans. In these plans the individual renewable energy targets for electricity, heating and cooling and transport sector are presented in detail. The technologies to be used, national policies and measures to develop cooperation between authorities are covered with these plans. (2009/29/EU 2009)

The Energy 2020 strategy has been implemented since 2007. In the past decade a lot of progress has been achieved. According to emission projections by member states the EU will achieve its overall GHG emission reduction target of 20%. Most probably emissions will even be reduced by 21%. (European Commission 2012) As can be seen from figure 5, some of the member states have already exceeded their targets for 2020 and many are very close. Already in 2014 the renewable share was over 15%. Broken down in to sectors, in heating and cooling the share was 17%, in transport around 6% and in electricity production 26%. Projected percentages for 2020 are 21%, 10% and 34% respectively and in total this adds up to 20%. (European Commission 2015c)

Although the EU is on track with these two targets, many issues are still present. The problem is great variance in progress between the member states. Figure 5 shows that while for example Sweden and Finland have exceeded their targets already, many are far from the targets. Malta, the Netherlands and the UK are still lagging behind and measures must be taken by these member states to reach the targets. Same problem lies with the emission target. Other countries are doing significantly better in achieving and exceeding the targets. At least Slovenia, Hungary and Czech Republic are falling behind. Projections still show that both of these targets will be met collectively, thanks to the member states that exceed their targets massively. (European Commission 2012)

Energy efficiency progress on the other hand is most likely going to fail the 20% improvement target. The member states have still been able to narrow the gap between the target and realized improvements. The expected efficiency improvements achieved in 2020 will be around 18-19%. In 2009 the projected energy savings percentage for 2020 was only around 10% (European Commission 2014a) Falling behind in the efficiency targets is because of poor economic performance and poor implementation of legislation. It would still be possible to reach this target if all member states would implement all of the existing legislation regarding to energy efficiency. (European Commission 2012)

The Energy 2020 is a first major step towards Energy Union and common management of the energy issues. The energy 2020 strategy includes the targets of the Energy Union, security, sustainability and competitiveness. Framework has been established to enable future development towards 2030 and even to 2050.

2.3.2 Energy 2030

Implementation is well in progress and targets already within reach for Energy 2020 strategy. Taking into account the current economic situation as well as situation in global energy markets, new plans have to be made to continue developing secure, sustainable and competitive energy system. Energy decisions and policies tend to have long lasting affects so planning well ahead is crucial. The energy policies and changes in them have an effect on investors' risk. Thus making commitments far in to future reduces the risk and promotes investments in the energy sector. The Energy 2030 strategy had to be made ambitious enough to set the pace for reaching energy targets also in the future. This strategy needed to promote less regulation and more flexibility to enable transforming to more carbon free energy system in a cost-efficient manner. (European Commission 2014b)

The Energy 2030 plans are a continuum of Energy 2020. Basis of the new strategy is that existing 2020 plans are fulfilled completely. The 2030 plans are meant to set the course for future development and continue the positive progress that has been achieved with previous plans. Intent is to aim even higher and learn from previous mistakes. New targets have been set for the share of renewable energy in consumption, energy efficiency improvements and greenhouse gas emission reductions. (European Council 2014)

Greenhouse gas emissions will be reduced by 40% compared to 1990 level by the year 2030. Continuous efforts are required to meet this target, but only by implementing the 2020 measures fully, reductions achieved by 2030 will be already 32%. Additional reductions will be achieved by ETS and non-ETS sectors together. Non-ETS sector will have to reduce emissions by 30% and ETS sector 43% compared to 2005 level to meet the target. Cost-efficiency is emphasized in the measures to reduce emissions. (European Council 2014)

Emissions trading system will go through some changes to achieve the reductions. One of these changes is reduction of cap or maximum amount of emissions allowed in EU area. New yearly reduction is 2.2% instead of 1.74%. This change will be implemented in 2021. (European Council 2014)

There will also be changes in allocation of emission permits. Although free allowances will still exist after 2020, they will periodically be reviewed. Giving free allowances especially to less wealthy member states will prevent carbon leakage, i.e. transferring of emission intensive companies to areas with lower cost of emissions, to those countries. Anyhow, the ETS is currently lowering the amount of free allowances significantly. Only the member states with a GDP per capita below 60% of the EU average have the opportunity to offer them. These countries are also limited to maximum of 40% free allowances. (European Council 2014)

Reductions in non-ETS sector are going to be made the same way as in previous framework. National targets for reduction are set for each member state. These targets are based on member states' relative GDP and they vary between 0% and 40% reductions compared to 2005 levels. Big emphasis is put on transport with regard to emission reductions. Through electrification and biofuels it is possible to achieve great reductions in emissions and also gain independence from fossil fuel suppliers. (European Council 2014)

Renewable energy has a key role also in the 2030 strategies. Increasing the share will not only help achieve secure, sustainable and competitive energy system. It also reduces EUs trade deficit in energy products, reduces risk of price variance of fossil fuels and creates jobs all over the EU. Renewable energy support schemes will continue to exist. In the previous framework the supporting the increase of renewable production was done mainly on country level. This had benefits in adapting to regional specificities but lacked cost-efficiency. In the 2030 plan the support schemes are transferred to be more EU driven. Cost-efficiency is taken in account more and more in planning and supporting new investments. Renewable technologies are supposed to be exploited where they are most feasible. (European Commission 2014b)

New target for share of renewables in consumption is 27% in 2030. This target is binding only at EU level. The GHG target of 40% itself encourages the member states to implement more and more renewable production capacity. The need of binding national targets was not seen mandatory. This gives the member states flexibility in meeting GHG reduction targets more cost-efficiently. It would also give room for the member states' own more ambitious targets for renewable share. As more renewable energy is implemented, emphasis on the integration of energy system is increased. (European Commission 2014b)

Increasing renewable share brings challenges to energy system especially when production is variable i.e. wind and solar power. Current state of the grid has been sufficient to support the 2020 target of 20% renewable share in European energy system. As planning goes on to 2030 and even further and the share of renewables grows even higher investments to grid infrastructure will become even more crucial. Creating an internal energy market to enable growth of the share of renewables is one of the key factors in this and also longer term plans. More interconnections, smart grid technologies and cooperation between the member states is required for this to happen. (European Council 2014)

For energy efficiency the plans are not that ambitious. An indicative target of 27% improvement in energy efficiency has been set but it is not binding at EU at country level. Cost-efficiency and competitiveness is much more valued in the current economic situation. Energy efficiency as well as renewable targets are going to be mainly achieved by reaching GHG emission targets. It is estimated that only by following guidelines provided with GHG reduction target an improvement of 25% in energy efficiency could be achieved. (European Commission 2014b)

The Energy 2030 strategy, if implemented as planned, will launch the development of EUs energy sector to a new level. This plan will continue the positive development achieved with the Energy 2020. At the same time looking a bit further. Plans made now will have an effect also beyond 2030. It provides the necessary framework also for the future and even more ambitious energy targets.

2.3.3 Energy 2050

The Energy 2030 strategy is the first leap taken towards low-carbon economy described in the Energy Roadmap 2050. This plan indeed has very ambitious in energy and climate targets. The problem with this roadmap is that it is almost impossible to predict with a reasonable accuracy the situation in 2050. Technological developments, economic and political situation and many other variables have an enormous effect on the development of energy sector. That is why diverse scenarios must be taken into account when planning in more detail. Also a lot of guesses and predictions have to be made.

Therefore in the Energy Roadmap 2050 the implementation of the roadmap is not yet planned very elaborately. Although the roadmap provides clear targets and presents different scenarios for the future, it does not go into detail about reaching the targets. Planning the detailed implementation will be done later, when the development of the variables that steer the energy sector can be more accurately evaluated. This roadmap lists also challenges that might prevent the EU from reaching the targets.

The Energy Roadmap 2050 has only one major target: an 80% cut in the GHG emissions by 2050 compared to 1990 emission levels. Other benefits are gained through reaching this target. The share of renewables must be increased and energy efficiency promoted in order for this target to be reached. Other specific targets are not set because it is impossible to predict how different technologies and their costs will develop over several decades. If electricity production with renewables is more expensive than carbon capture and storage (CCS) technologies, the renewable share may stay lower. Cost-efficiency is crucial for reaching competitiveness of the energy system so GHG reductions must always be done the cheapest possible way. (European Commission 2011a)

The EU has set different milestones for the path to accomplishing the emission reduction target. The reductions should be 40% by 2030, which is already set in Energy 2030 plans and 60% in 2040 compared to 1990 emission levels. Steady reduction pace would prevent haste when the 2050 is closing in. Reductions made earlier for example through energy efficiency would lead to notable savings in the future. (European Commission 2011a)

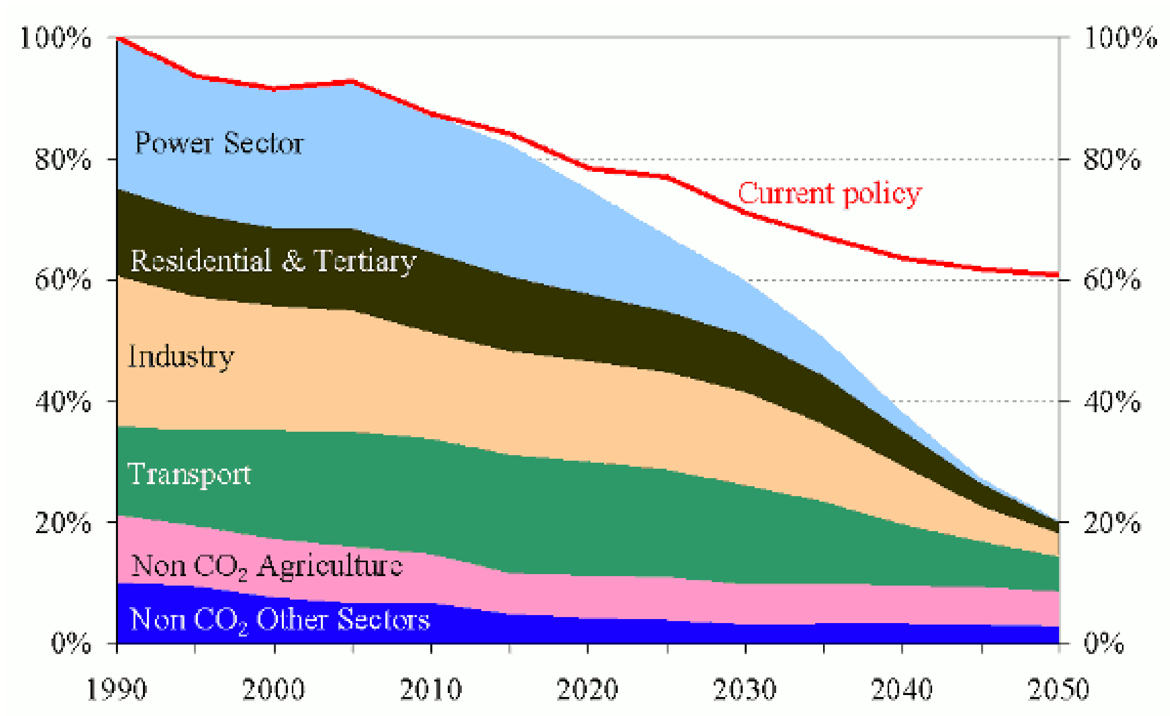


Figure 6: CO2 reductions by sector from 1990 level. (European Commission)

The Energy Roadmap 2050 evaluates where the reductions in GHG emissions could be made. It is certain that all sectors must participate in order for this plan to succeed, but some sectors may have more potential to cut the emissions than others. This can be seen from figure 6. In almost all of the sectors the reductions that are required are rather drastic. Power generation and distribution has largest potential in GHG reductions. Almost all power could be made from renewable sources and fossil fuels have to be used only in extreme conditions. For this to happen, major leaps in storing electricity have to be made in order to provide sufficient balancing for the variable renewable sources. Also CCS technologies could be key to massive reductions. (European Commission 2011a)

Great reductions could also be made in industry and buildings. More than 80% reduction in emissions could be reached in both of these sectors. In buildings the reductions can be made by improvements in efficiency of the appliances, use of passive housing technologies and using renewable sources for heating. In the industry sector the reductions can mainly be made through cleaner and more efficient technologies. Later, nearing the year

2040 CSS could also play a part especially in emission intensive industries. (European Commission 2011a)

In transport sector the usage of electricity as power source should be increased. Emissions could be reduced up to 60% in transport by increasing the share of hybrid and electric cars. Also biofuels have an important role in emission reductions. Heavy vehicles and aeroplanes cannot be run on electricity and biofuels could be a solution for those to gain the reductions. In agriculture the reductions will be based on cuts from fertilisers and livestock. Agriculture could be also a part of CCS as soil and forests could be used as storages for CO_2. (European Commission 2011a)

As said before the development affecting energy sector will steer the measures taken to reach the goal. Different scenarios that predict the possible changes in the energy sector have been made as a part of the Energy Roadmap 2050. There are altogether seven of these scenarios. Two of which, the Reference scenario and the Current Policy Initiatives, reflect current trends. The rest, High Energy Efficiency, Diversified supply technologies, High Renewable energy sources, Delayed CSS and Low Nuclear are so called decarbonisation scenarios. (European Commission 2011a) Some common factors join all of these scenarios. That is to say that these factors will most probably realize in a way that has an effect on the European energy system.

First of the ten common factors is the decarbonisation. Different scenarios show that this is indeed possible and will be realized in the future. What is surprising is that the cost of decarbonisation is not that high. The cost of five decarbonisation scenarios do not differ much from the Current Policy Initiatives scenario. The scenarios also tell that overall the fuel costs will become lower and capital costs will increase in energy sector. As more and more energy will be produced using renewable sources that usually have low of even non-existent fuel costs, the overall fuel costs will decrease. On the other hand the infrastructure investments that need to be made in production equipment, renewing the grid and storing electricity will grow. (European Commission 2011a)

Electricity will have more and more share in final energy demand in the future. It is estimated that in 2050 36-39% of the final energy consumed will be in the form of electricity. Electricity will have a much greater role in for example transport and heating and cooling. Most of the scenarios predict that the price of electricity will rise until 2030 and then start to decline. The initial rise is mainly caused by need to renew old infrastructure in the next two decades. A large portion of production capacity as well as grid infrastructure have come to the end of their life-cycle. Renewing of them will have an effect of the cost of electricity. One common factor in all of the scenarios is that the demand of energy will grow. This will also have an effect on the electricity prices. (European Commission 2011a)

To reach the targets set by the Energy Roadmap 2050 both energy efficiency and the share of renewables will increase substantially throughout the scenarios. Energy efficiency must be improved by 16-20% by year 2030 and 32-41% by 2050 from current level to reach the targets for GHG emissions. The renewable share should increase at least to level of 55% by 2050. This is why setting up specific targets for these two factors was not seen mandatory. (European Commission 2011a)

CCS will play an important role in transforming the European energy system and reducing emissions. In almost all of these scenarios, except the High RES scenario CSS had key part in reaching the targets. Nuclear energy is also in a vital position in the scenarios. In many member states it remains the single biggest source of low carbon electricity generation.

Final common factor in the scenarios was decentralisation of production. Renewable energy sources are available almost everywhere and in pursue of the emission reductions, the source must be utilized in various places. All of the production must still be able to work together to ensure security of supply. That is why the control over various production sites and methods must be somehow centralized. (European Commission 2011a)

The Energy Roadmap 2050 provides not so much answers to specific problems or detailed action plans for the future. It is more of a map that can be used as a basis for future plans that will go more into detail. It provides different paths that may be the course of the development in the future. But as it is impossible to know for sure it is futile to plan too carefully. The Roadmap still gives clear and ambitious guidelines for the member states to aim for.

2.4 Summary of the EU Energy strategies

The European Union has set an impressive set of targets steering the development of energy sector. Creating sustainable, secure and competitive energy system that ensures affordable and clean energy for all EU citizens is the main priority of the Energy Union and all of its strategies. Key development targets can be seen from table 1 below. First steps have been taken in a form of Energy 2020 strategy implementation but a lot remains to be done if the EU wants to be the forerunner in energy sector.

Table 1: EU Energy targets. (European Commission 2011a) (European Commission 2012) (European Commission 2014b)

Target	2020	2030	2050
GHG reduction	20%	40%	80%
Energy efficiency improvement	20%	27%	-
Renewable share	20%	27%	-

The internal energy market, the great enabler of all these plans, is still a work in progress. Increased cooperation is crucial for an energy system this big to work. A lot of investments are required on the infrastructure around EU area to provide new and more environmentally friendly production capacity. Investments are also needed to improve the grid to remove barriers between countries and physically make the EU a single market area. Altogether 270 billion euros or 1.5% of GDP annually is required to make these investments over the next decades (European Commission 2011a). Policies are to be made on EU level to ensure equality between the stakeholders and reduce the risk of policy changes.

It is important to stay on track in the early stages of this development towards 2050. Change does not come easy and future development of technologies is impossible to predict. The development must start now rather than waiting for some technology to step in at the last moment. If these plans are to be fulfilled properly, it could mean a great deal to the EU for a long time. Boosting research and investments in energy business improves the economic situation and brings jobs to Europeans. Dependency on others in energy sector would be reduced to near zero in the next few decades. Also health benefits can be achieved through less pollution. So the huge investments made will be paid back.

These strategies will be the basis of this thesis as they show the direction towards which the EUs energy sector is aiming for. As energy emissions targets are hard to simulate, this study will focus on development of the energy mixes, production, demand and interconnection capacities. A big emphasis is put on increasing share of renewable production. Especially the variable renewables such as wind and solar power as they tend to put pressure on the energy system. Physical development of internal energy market is also investigated in detail.

3 European electricity grid

The electricity grid is probably the single most important tool in enabling the transformation of the European energy system. Well-functioning grid allows more flexibility in production methods, increased competition and better security of supply. In other words efficient grid provides sustainability, security and competitiveness that the EU energy strategies long for. As grid improvements are a vital part of European energy strategies, it is important to understand the situation today and how thw EU will promote development of the grid in the future. In the following chapters the European electricity grid and its development are studied. First the situation today, weak points and challenges for development are investigated. Then plans for the development of the grid are presented and finally key findings are summarized.

3.1 European electricity grid today

The European community has strived for integrating the electricity grid and building common electricity market for decades. Moving from a world of natural monopolies and bilateral trading to the modern open electricity markets and trading though power exchanges has proved to be beneficial. The old state owned energy companies that owned both production and transmission infrastructure have undoubtedly been inefficient and costly compared to modern alternative. As liberalization of the markets has increased the old, mostly state owned energy companies have had to make way to modern energy companies that compete in international markets. (Bacon, Breasant-Jones 2001)

A lot has been achieved. The integration of the market, both physical and regulational, has had a clear effect on the wholesale electricity prices. They have steadily declined as the integration has progressed. Legislations have been set to free the markets from monopolies. Competition has increased which means more choice of supply for the customers, better services, cheaper prices and increased supply security. More money has also been used for grid improvements since strive for reaching new customers has increased. (European Commission 2015b)

Although many improvements have been implemented successfully, a lot still needs to be done in order to reach single pan-European electricity market. Completion of the internal energy market is top priority of Energy Union. Import dependency is still very high. This causes lack of supply security in case of political disturbance or faults in supply lines. Several member states also lack interconnections between neighboring countries. This increases risk of power shortage in case of sudden shutdown of large production units. Principal of solidarity is tightly connected to the strategy of the Energy Union. Without seamlessly connected energy market the member states cannot rely on each other to help in the time of sudden outages or other disturbances in the grid. (European Commission 2015b)

A great deal of grid infrastructure has come to an end of its lifetime. Renewals must be done to keep the connections working and prepare them for upcoming changes in production mix. European Commission estimates that investments up to 200 billion euros are needed to create enough infrastructure. Contributions are needed, in addition to building new connections, for example in software updates and metering devices to be better able to control and monitor the complicated electrical systems. (European Commission 2015b)

Increasing amounts of renewables will put an unforeseen strain on the transmission grid. The new infrastructure must be able to handle this stress. The EU strategies suggest huge increses in the renewable share. The magnitude of the increase is so high that the grid today couldn't endure it. Daily variations in the amount of wind and sunshine can rarely be accurately predicted. If large capacity of for example wind power is installed and the wind speeds suddenly drop the risk of instabilities to the grid is remarkable. (Lew, et al. 2009) It is vital to build the grid in a way that the instabilities in certain areas can be eliminated or reduced by importing from other areas. This way the security of supply can be ensured while increasing the amount of renewables.

To deal with these concerns and to complete the internal electricity market the European Union has set a target of reaching 10% interconnection rate between member countries by 2020. A further target of 15% by 2030 also exists. The interconnection rate means the amount of interconnection capacity in relation to electricity production capacity. So the more production capacity a member state has the more interconnection capacity is required. The main focus of the grid extensions inside the member states and cross-border connections should be focused to the countries with lowest interconnection rate. A list of countries and their interconnection rates in year 2014 is found from table 2 below. (European Commission 2015b)

Table 2: Interconnection rates in EU countries in 2014 (European Commission 2015b) *) before completion of Estlink 2.

Member states above target	Interconnection rate %	Member states below target	Interconnection rate %
Austria	29	Ireland	9
Belgium	17	Italy	7
Bulgaria	11	Romania	7
Czech Republic	17	Portugal	7
Germany	10	Estonia*	4
Denmark	44	Lithuania*	4
Finland	30	Latvia*	4
France	10	United Kingdom	6
Greece	11	Spain	3
Croatia	69	Poland	2
Hungary	29	Cyprus	0
Luxemburg	245	Malta	0
The Netherlands	17		
Slovenia	65		
Sweden	26		
Slovakia	61		

As can be seen from the table 2 above the 10% interconnection target is not that easily reached. While some member states are already well above the target, some are far behind. In total 12 of the member states had not yet reached the 10% limit. However the completion of Estlink 2 cable between Finland and Estonia with additional 650 MW capacity implemented in February 2014 lifted the Baltic countries to around 10% interconnection rate (Fingrid 2014). The Baltic countries Estonia, Latvia and Lithuania are still desynchronized from other Europe and thus handled as one. Completion of LitPol between Lithuania and Poland and Nordbalt 1 connection between Sweden and Lithuania have later increased the rate for the Baltic countries even higher. Yet nine member states exist, some of them major ones, with under 10% interconnection rate. With less than 5 years to reach the target, reaching it seems unlikely. (European Commission 2015b)

Member states with lowest interconnection rates are mainly islands such as UK and Ireland or located in peninsulas such as Italy, Spain and Portugal. These member states are isolated from their neighbors geographically as well as electrically. Two of the islands, Cyprus and Malta, are completely cut off from other countries. They have no connections to other countries and have a zero interconnection rate. On the other hand member states that have many neighboring countries, those in Central Europe have usually much higher interconnection rates. Most of them have rates well over 15% rates, so they have already met also the 2030 target. Nordic countries, Sweden, Finland and Denmark have also high interconnection rates. That is mostly because of large amount of hydro power imported from Norway to and through these countries.

Connecting the isolated areas is a big challenge and requires a lot of investments. However it is vital if the EU wants to reach its visions for 2050. A great deal of the member states that are isolated are in the southern part of Europe. Those states also have a lot of renewable production potential which is vital for EUs energy strategy to become reality. Just reaching 10% interconnection rate will not be enough but even more ambitious plans are needed. Europe's energy islands Malta and Cyprus are more easily handled due to small production. Only one rather small connection could increase interconnection rate to well over 10%. (European Commission 2015b)

Cross border connections are not the only connections needed to complete the internal energy market. Many member states have also weaknesses and bottlenecks withing their internal grid. Reinforcing internal connections is vital for free energy flows through Europe. In order to enable large amounts of renewables, the member states will need a lot more transmission capacity especially in north-south directions. That could ease the utilization of solar capacity in the South as well as hydro and wind capacity in the throughout the Union. (European Commission 2015b)

3.2 Grid development

European electricity grid is in dire need of drastic development. In order to be able to handle the changes the European energy system is going to face over the following few decades, big contributions are needed in physical grid infrastructure. Improving the grid itself and increasing capacities with current technologies is not nearly enough. Legislation and regulations are needed to speed the implementation of grid improvement projects. The way that the energy is produced and the grid is controlled must also be thought of in a completely new way. More control must be handed over from regional regulators to joint operator.

Many of the existing plans draft a roadmap towards an internal energy market in Europe. The European network of transmission system operators for electricity (ENTSO-E) makes The Ten Year Network Development Plans (TYNDP) which are updated bi-annually. These plans are the EUs official blueprints that are followed to reach the 10% target. It also includes Projects of common interest (PCI) which are the prioritised projects to reach the target. TYNDP plans and PCIs will be investigated more in detail later in this chapter. Despite careful planning it is quite impossible to predict the future of the grid far ahead because of the new technologies that might break through. Developing smarter grid technologies is crucial as old technologies might just not be enough in the future. That is why in the following pages some plans and technologies are presented for making the grids more able to handle the future developments.

3.2.1 Making the grid smarter

The European Union has identified current grid solutions as inadequate when planning the new energy strategies. Just adding capacity is not nearly enough. Grids must be more easily controlled, monitored and optimized to handle various small and dispersed production units as well as big conventional power plants. Energy flows must be more easily channelled to ensure that the target of energy security is met. An energy system that spans throughout Europe must be smarter and more flexible in the constantly changing environments. As the future cannot be predicted the grid must be elastic to be able to meet future challenges.

Smart grid includes a multitude of different technological solutions that increase for example automation, remote control possibilities and metering of the electrical grid. These are for example different kinds of metering devices, relays and computer systems that reduce the need for manual data gathering or even outage repairing. Two way communication is essential for smart grid technologies. It can be used to read sensors remotely and even repair the problems in the grid. Utilization of these technologies span through whole energy system, from production unit's through transmission grid and all the way to end-user. (Sarvaranta 2010)

Smart grid is not only existing in the visions of researchers but it is rapidly becoming a part of today's modern electricity grids. As grid renewal projects are implemented, new devices that add "smartness" to the grid are installed. Technologies such as remote metering systems and automatic failure detection are already used in many grids. As the evolution of the smart grids progresses and the various technologies are applied in full, the possibilities are much greater. Adapting electrical vehicles as an electricity storage in the grid or selling solar power produced in your back yard becomes reality. (Sarvaranta 2010)

Smart metering systems are the forerunners of the smart grid technologies. They are deployed already today all over the world. Smart metering systems have proven to be a feasible solution to increase efficiency in data gathering. (EEI-AEIC-UTC 2011) Smart metering technologies can be used for example by end users to follow consumption, to monitor the condition of the grid by measuring current or to direct the load to prevent cut-off. All this can be done remotely. Smart metering also gives the end-user of electricity the possibility to monitor their electricity use. (van Gerwen, Jaarsma, Wilhite 2006)

The benefits of smart metering are multiple. It gives real time information on the condition of the grid without the need to go on site. This information can be used to better plan production and respond to sudden changes in consumption. This eases optimization and makes the whole energy system more efficient. Security is improved when metering is used to alarm the system operator about instabilities in the grid and respond before outage is unavoidable. Adjusting demand to match production or demand respond can also be executed using smart metering. Voluntary or forced limitation of consumption could be used to provide more flexibility in varying production situations. This would further ease the implementation of renewable energy. (van Gerwen, Jaarsma, Wilhite, 2006). Pan-European electricity system would benefit significantly from the increase of smart metering. Real time consumption and flow information would make controlling the system easier. A large system with multiple producers and consumers would also gain savings when allocating payments for electricity (Sarvaranta 2010).

Smart metering provides a starting point for developing other smart grid systems. Different automated technologies and controlling systems use the data from smart metering systems to provide system operator with more control over the grid. Automated failure detection and alarming systems can easily be added to metering systems. Automation can also be used in case of imminent network failure to automatically isolate a part of the grid to stabilise the rest. (Choi, et al. 2011). These possibilities can increase the supply security. With two way communication systems controlling various distributed production units becomes possible (Sarvaranta, 2010). This can further help balance the system and optimize the production. In case of varying wind or solar conditions remote controlling systems could be used to start alternative production units to prevent lack of power in the grid.

With currently available technologies, electricity is difficult or not cost-efficient to store. Same amount of it must be produced as is consumed if wasting electricity and thus reducing efficiency is not an option. Fully accurate forecast of demand and production is impossible to have. That is why the situation in most cases is that excess electricity is produced to prevent causing instabilities to grid with shortage of power. This of course leads to inefficiencies in the power system. The fact that further complicates balancing the electricity system is variation in demand. Demand varies depending on the weather conditions, time of the day and many other factors. (Feinberg 2012) An example of daily variation can be seen in figure 7. The figure shows two peaks. One, the higher, in the morning and another in the evening. This pattern follows the daily schedule of most people. Lowest point is at night when most are at sleep. Steep rise in the morning as everyone wakes up and second peak after people come home from work. Responding to these radical variations is difficult with technologies used today.

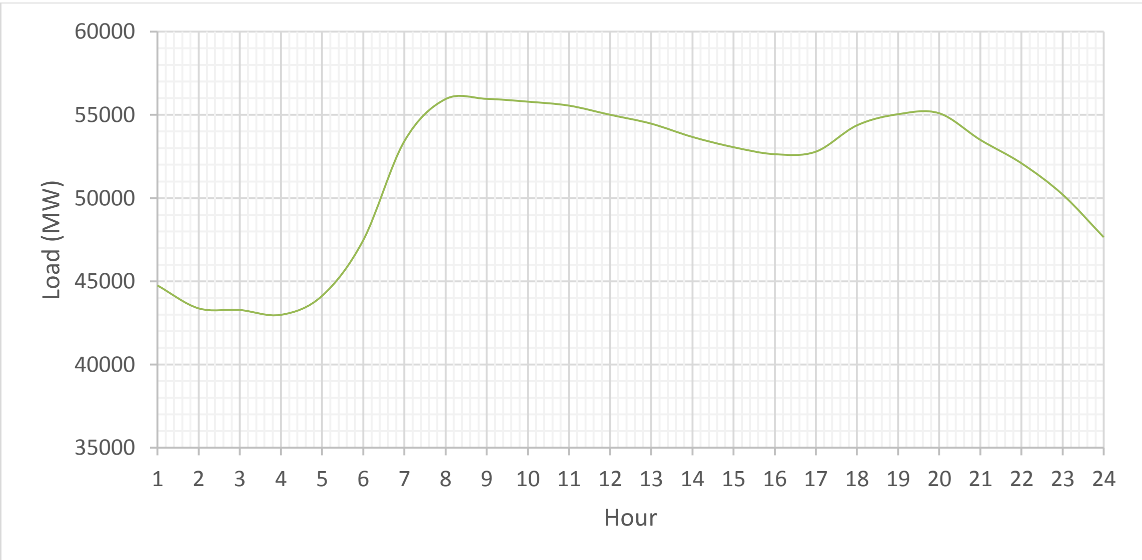


Figure 7: Hourly demand curve in Nordic countries 11.3.2016 (Nord Pool)

On the other hand production is increasingly non-flexible. The amount of electricity produced using variable renewables is rarely adjustable. Production amounts depend mostly on the availability of the resource. With both demand and production varying constantly, optimization of the electricity system becomes crucial. Smart grids and new metering and control technologies allow much more accurate optimization of the demand and production.

Using metering data and control technologies combined with load and weather forecasting, great efficiency improvements can be made. (Aula, Lee 2012) As demand usually follows the daily pattern of peaks and off-peaks seen in figure 7 it would be useful if this pattern could be broken. In other words, shaving off the high peaks and using the load more evenly. Using for example appliances such as dryers or dishwashers during the off peak at night, the morning peak could be evened out (Aula, Lee 2012). Smart grid technologies could turn on some loads when demand is usually lowest automatically and on the other hand switch off some loads when demand is rising. By that kind of control the grid would be less affected by variations.

Other method for balancing out the peaks is storing electricity. As stated before the storaging technologies are currently not feasible enough because of lack the required capacities to control load profiles in a required manner. Nonetheless it is certain that in the future electricity storing will be an inseparable part of the energy systems. There are already many different methods of storing electricity. Technologies vary from simple batteries and flywheels to supercapacitors and pumped hydro storages. They vary a lot depending on the storing capacity and rate of discharge and time of storing. The biggest energy storages are up to one GW in capacity and can store this energy for several days. However even higher storage capacities and longer storage times are required to use these technologies as a serious balancing or back-up system. (VTT 2009)

Using smart grid technologies to balance the loads in addition to storing could help a lot in integrating large amounts of renewables. Loading storages full with renewables during early hours of the day and discharging the batteries when evening peak comes would balance the system. In figure 8 is an example of such balancing. Water heating, AC usage and other appliances that are not needed at a certain time are mostly used when the solar energy is at its peak, the yellow line. Batteries, the green areas, are loaded when there is excess production during the high solar production and discharged in the evening to reduce the need for additional production. (Dyson, M. Morris, J. 2015)

A lot can be done using smart grid technologies. Load controlling can balance out the variations brought by new renewable capacity and increase efficiency in the energy system. Security of supply is increased due to real time data on the condition of the grid.

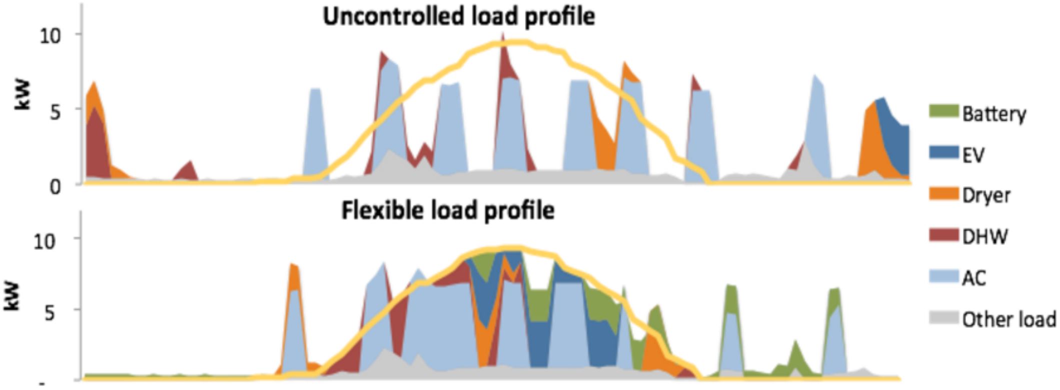


Figure 8: Example of uncontrolled household load and balancing with storages and load controlled devices. (Dyson, Morris 2015)

Unfortunately the European grid is not yet smart enough to deal with upcoming changes. Major increase in storage capacity could resolve many problems that future has to offer. But the fact is that in Europe, the leader in storing capacity, only 6% of total capacity can be stored (VTT 2009). Using of electric vehicles as an electricity storage could change the situation but still a lot remains to be done to equip the grid with technology that can handle future energy visions.

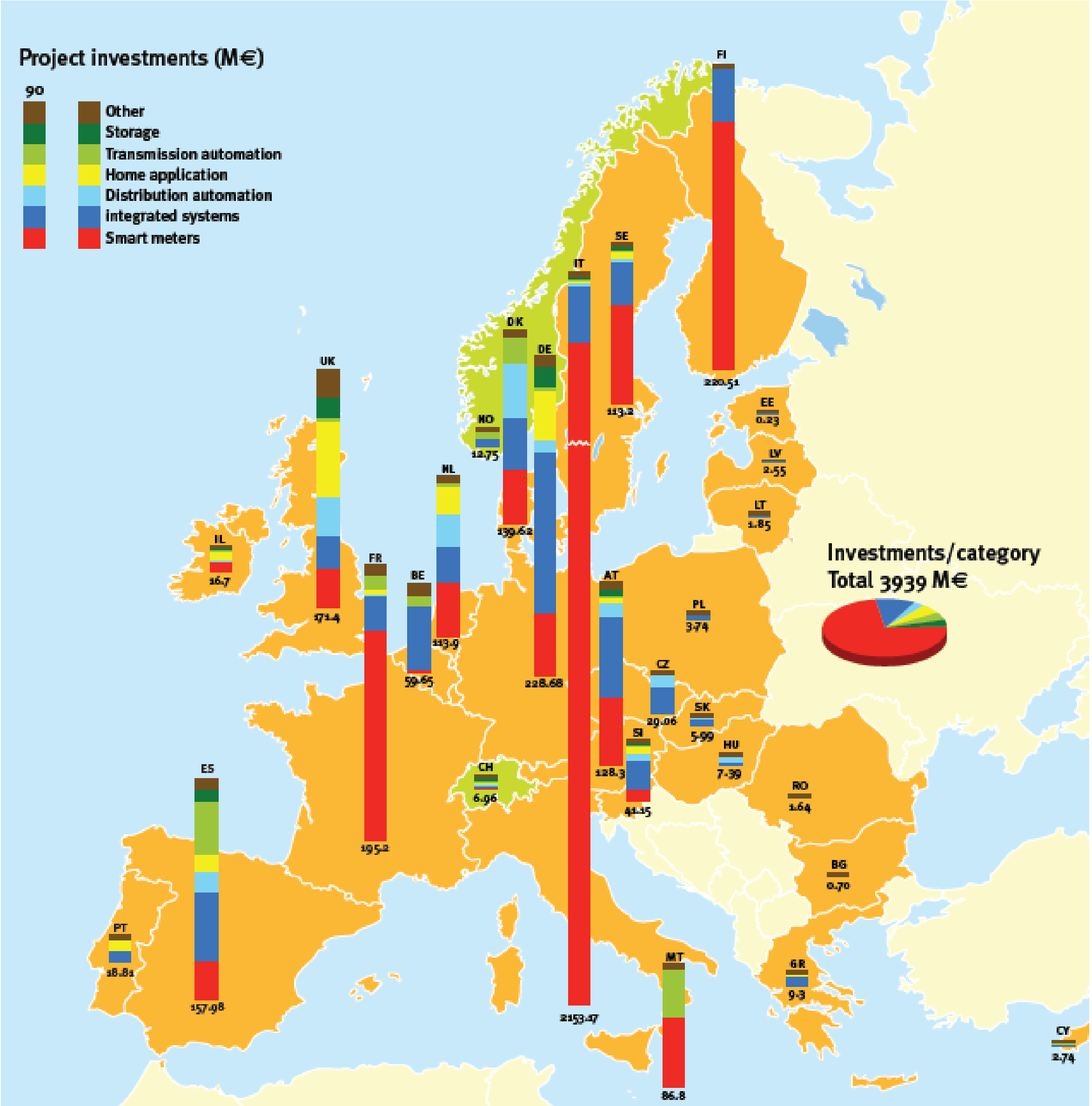


Figure 9: Investments in smart grid projects in Europe 2011. (JCR 2011)

A lot is happening in the European Union to develop the required technologies. The Joint Research Centre (JRC) is the technical and scientific section of the European Commission. It provides researchers around the EU with advice and know-how which supports EU policies. The JRC has identified as one of its priorities to support research related to creating smart electricity systems. Total number of 459 smart grid projects have been identified since 2002. Their monetary value is over three billion euros. European commission is funding these projects by covering approximately one fifth of the total budget. The majority of the funding originates from the private sector. (JRC 2014)

Investments in smart grid projects divided by type of technology are presented in figure 9 above. The vast majority has been used to smart metering projects as it is the most widely used in the current grids. In UK big investments have also been put to home appliances. Investments in storage technologies were low in 2011 but will surely rise in the next decades. Since 2011 investments have been focused a bit differently. Customer and domestic appliances have a much bigger share now. Also many electric vehicle investments have been made especially in Germany and Austria. In those countries these investments make up the majority of all investments. (JRC 2014)

The European Union is firmly pushing research and development efforts to transform its electrical grid to match the needs of this century. This task is not an easy one. Traditional grid design with large centralized power stations, ageing infrastructure and limited connections to other areas optimized technologically to serve only small areas needs will have to evade. (JRC 2014) In the constantly changing technological and political environment a new smarter grid with more flexibility is required. It is a key in building secure, sustainable and competitive pan-European energy system.

3.2.2 ENTSO-E plans for grid development

Long term centralized planning of network development is crucial in building a pan-European electricity network. Joined planning and focusing of resources is a requirement in this effort. Responsibility of delivering these plans has been given to ENTSO-E (347/2013(EU) 2013). Since 2009 ENTSO-E has been publishing the Ten-Year Network Development Plans which steer the development of the grid from EU level to a single member state. These plans are published every other year to sufficiently respond to newest technological and economical changes. Main goals of the TYNDP is to maintain supply security in every part of the grid, enable reductions in GHGs and build the European internal energy market. (ENTSO-E 2014)

The development of the grid is playing a big part in this study. The success of the EU plans is highly dependent on the grid development. These TYNDPs are the official EU policy on future development. That is why thorough knowledge of these plans is vital for understanding the future of the European electricity grid. These plans include assessments of the grid infrastructure today, its weak points and condition. They also make predictions for the development of energy sector for the next ten years and even further. Changes in production mixes, demand of electricity and development of new technologies related to grid are estimated. Different scenarios are made for the future. (ENTSO-E 2014)

These scenarios are used to determine how to develop the grid in the next ten years and how to best use the resources available. Hundreds of different projects are assessed based on these scenarios to select the most important ones. These projects called PCIs or Projects of common interest are the most important when it comes to reaching EU energy targets and creating European internal energy market. They include a variety of storage and transmission development projects. (ENTSO-E 2014) Plans are taken to member state level in regional investment plans, in which more detailed regional development over the next ten years is presented. Regional investment plan for the Baltic Sea region is presented later in this chapter.

The newest TYNDP 2014 tries to look a bit further to the future as previous ones. The ten year scope is extended to 2030 and multiple scenarios are presented for possible outcomes. The current situation of the grid is worrying. Rapid development of the grid is required to reach other EU energy targets, such as renewable share increase. A total of 100 bottlenecks have been identified in the EU area. The map in figure 10 shows the most problematic regions. These bottlenecks are or will be in the next decade the barriers for internal energy market completion. They lack transmission capacities to neighboring areas (blue, light blue and brown) or are going to face significant increase in production capacity (green). (ENTSO-E 2014)

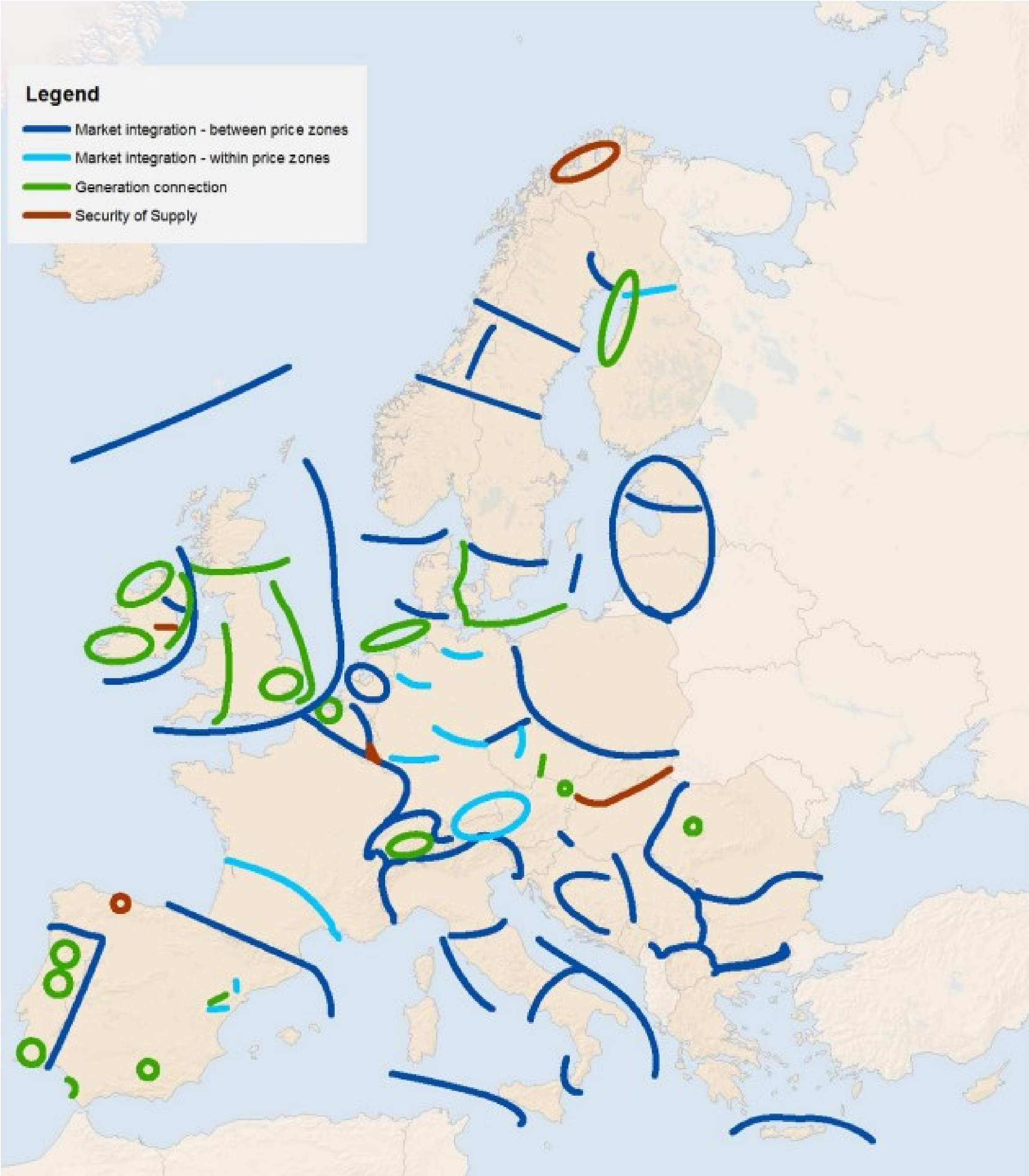


Figure 10: Main bottlenecks of electricity transmission in EU area in 2014. (ENTSO-E 2014)

Figure 10 shows that a lot of improvement is needed. Market integration between price zones marked with blue on the map is an issue practically everywhere in the Europe. Cross border connections to increase the transmission capacity are needed to balance the inequalities between areas. Boundaries marked with the light blue are in various places. These areas are lacking connections inside the regions. For example in Finland and Germany the growing North-South energy flows resulted by renewable energy production increase pressure to improve capacities also inside the regions. Though improvements have been made since 2014 to increase transmission capacity for example in the Baltics and between UK and continental Europe, a lot remains to be done.

On the peripheral regions there still are serious issues regarding security of supply. These isolated regions for example in the Northest part of Europe are too much relied on single transmission lines. Disturbances in a supply line may cause a cut-off in the whole region. Building more than one supply line to those regions is a vital to provide supply security to the whole system. (ENTSO-E 2014) On the coastal areas throughout the Europe grid improvements are needed to support upcoming renewable energy production. Grid connections to offshore wind production sites and reinforcement of coastal grids will be major investment target during the next decade. (Henderson 2003) Some of the boundaries between the areas are related to more than one of these issues. The most problematic areas are the Baltic States, Great Britain and Ireland, Italy and Iberian Peninsula. Connecting these areas to continental Europe solves multiple problems at once. (ENTSO-E 2014)

The outcome of all these pending investment is that if they are implemented as planned the interconnection capacity around Europe will double. This is mandatory if increasing power flows are to be transmitted efficiently around Europe. According to some scenarios even this is not enough. Development of electricity storing capacity could lessen the pressure to increase the transmission capacities. As there is not currently any alternative, large capacity increasing investments must be made. (Andersen, et al. 2014) The total budget of these investments is 150 billion euros. In return the wholesale power prices are estimated to drop 2-5 €/MWh around Europe. Approximately 80% of the projects in TYNDP 2014 are addressing the integration of renewables to the grid. By reinforcing coastal grid and thus enabling rapid increase of wind power, the power sector will be able to reduce 20 % of GHG emissions by 2030. (ENTSO-E 2014)

The ENTSO-E publishes in addition to the TYNDPs also regional plans. For better allocation of the resources ENTSO-E has divided Europe to six regions. Plans are made for each of them including for example challenges and special requirements in each of the six regions by 2030. The latest Regional investments plans were published in 2015. The Regional investment plans (RIP) on the Baltic Sea region is the most relevant grid development plan to this study. It is necessary to investigate this plan in detail to further clarify the current situation and the future development in the area in question.

The Baltic Sea region consists of nine countries. Nordic countries Finland, Sweden, Norway and Denmark. In the Baltics, Estonia, Latvia and Lithuania. In addition to these also Poland and Germany are a part of the Baltic Sea region. Though a part of these countries, such as Poland and Germany are partly included in other regions too, this plan describes the connections between these countries well. (ENTSO-E 2015a) Thus it is sufficient to investigate only the Baltic Sea region investment plan for the scope of this study.

The Baltic Sea region is further divided into areas, known as bidding areas, as seen in figure 11. Finland, Estonia, Latvia and Lithuania are each a single area. In this study Poland and Germany will also be considered as single areas. Sweden is divided into four, Norway to five and Denmark to two synchronous areas. Figure 11 shows also the capacities between the areas. The Nordic countries are well connected between each other and to the continental Europe. Denmark is gateway of electricity in the middle of the Nordic and the continental system. That is why the capacities to Germany are so significant. The Baltic countries are not very well connected to the rest of the region. Only one connection to Finland is shown on the map. The situation has improved since. Newly commissioned connections exist between Sweden area 4 and Lithuania called Nordbalt and between Poland and Lithuania called LitPol. Both of them were implemented in the end of 2015. (ENTSO-E 2015a)

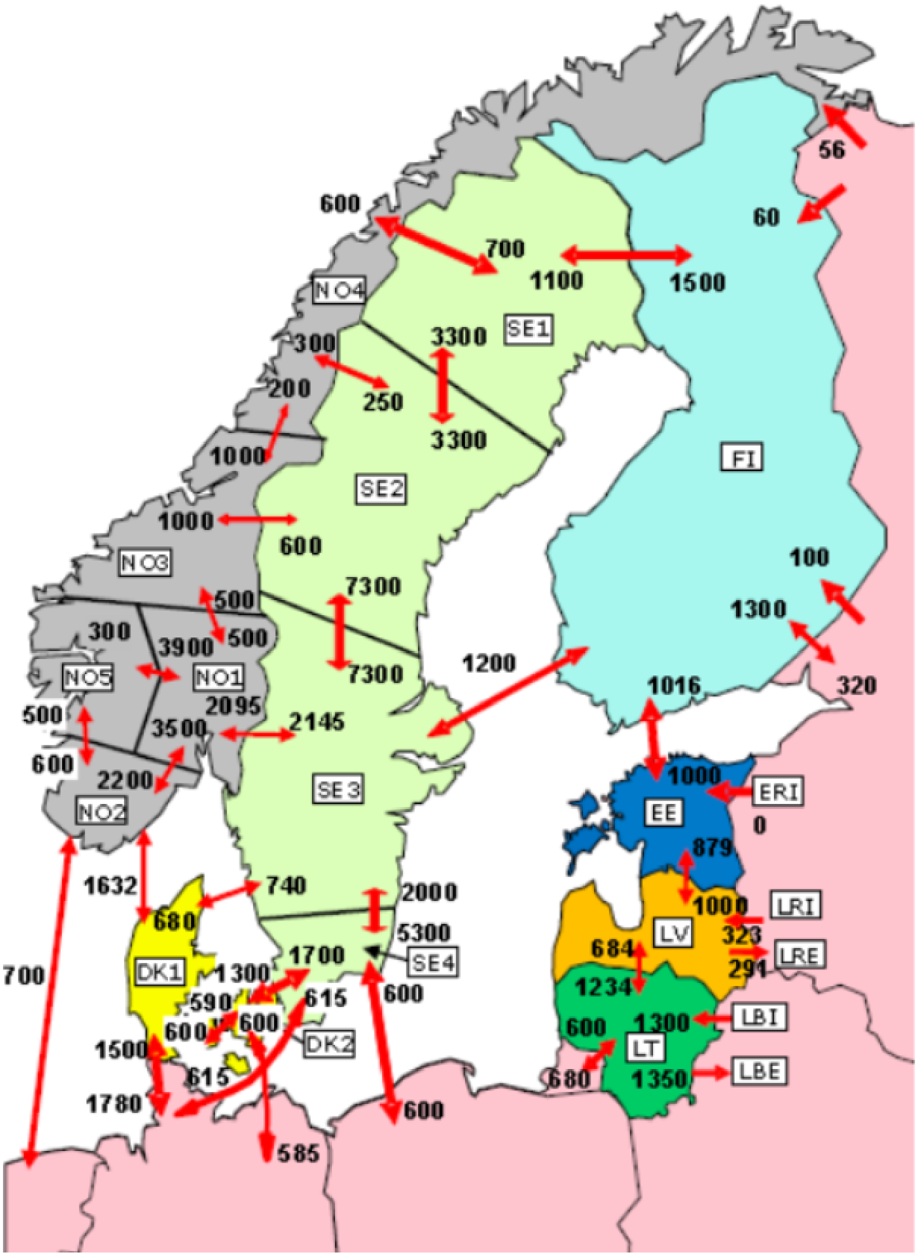


Figure 11: Map of The Baltic Sea region area and transmission capacities (ENTSO-E 2015a)

The Regional Investment Plan for the Baltic Sea region presents five different issues or incentives for grid investments for the upcoming decade. A part of these are common for the whole EU level and some are specific to the Baltic Sea region. One upcoming challenge that affects the Europe is the increase in the North-South flows. Efficient transfer of massive amounts of solar power from Germany to the Nordics during daytime and wind and hydropower from Nordics to Central Europe requires increased capacities. It is likely that transmission lines will be congested inside areas of Sweden, Norway and Finland. (ENTSO-E 2015a)

The Nordic countries have had energy surplus in the past. This situation will likely remain the same at least until 2030. The same North-South flows that congest internal transmission lines in the Nordics require also investments in interconnections between continental Europe and Nordics. This kind of development would also be beneficial for daily regulation of the electricity network. Hydro based Nordic system, thermal based Continental system and Danish wind based system would together create energy system that has a wide variety of different production methods. A system with such variety in production methods and efficient connections would be secure and stable. (ENTSO-E 2015a)

In the Baltic Sea region plans the arctic region cannot be forgotten. As seen in figure 10 the arctic area is lacking supply security and sufficient transmission lines so it remains an isolated region. Growing interest in the arctic region with massive resources could boost demand in the area rapidly in the next decades. The grid must be prepared for this kind of development. Another area in the Baltic Sea region that needs reinforcements in the interconnections is the Baltic area. Estonia, Latvia and Lithuania are behind the others in interconnection rate. In addition, the Baltic States are still synchronized with Russian power system. Having inadequate connections to the Nordics and Continental Europe and being asynchronized from rest of the Europe makes the Baltic countries highly dependent on electricity from non-ENTSO-E countries. (ENTSO-E 2015a)

Another thing to consider when planning future of the grid in the Baltic Sea region is decommissioning big production units. By 2030 in Sweden, Germany and Finland a big share of nuclear production capacity is expected to be decommissioned. Building new reactors is still uncertain with the low electricity prices. This could lead to system instabilities although the Nordics are still expected to have energy surplus in 2030. Grid investments are answering to all these issues but the grid would need renewing even without them. Majority of the grid infrastructure in the region is from 1950s and 1960s and in need of renewal. (ENTSO-E 2015a)

The RIP for the Baltic Sea region proposes multiple projects to respond to the developments in the energy sector in the following decades. The projects include renewals and improvements to old connections as well as building completely new ones. A part of the projects have already been accepted to the list of PCIs in TYNDP 2014. Others are still waiting assessment to be published in the TYNDP 2016. These projects are tested against different future scenarios to prove their feasibility. (ENTSO-E 2015a)

Connecting the Baltic countries to continental and Nordic system is clearly a priority. In addition to the recently commissioned connections, the RIP proposes further connections to be built. LitPol stage two and NordBalt phase two will increase interconnection capacity over 1000 MW. Connections among the Baltics is also reinforced by building third interconnection between Estonia and Latvia increasing the capacity by approximately 500 MW. In already strongly connected Nordics new connections are also proposed. Connections between Finland and Sweden areas 1 and 3 will boost the cross-border capacities by over 1000 MW by 2030. Connections are reinforced between internal areas in Sweden areas 2 and 3 and in Denmark. (ENTSO-E 2015a)

In preparation for the increasing amounts of renewable production, grid improvements are proposed heavily between the Nordics and continental Europe. Germany is being connected to Sweden area 3 with two connections Hansa PowerBridge 1 and 2 in different stages adding 1500 MW of capacity. Projects to further connect Denmark area 2 and Germany are planned as well. With improvements in current connections and building new

Kontek-3 line the capacity would grow 1600 MW in the next few decades. Many grid improvement projects also aim to reinforce grid to enable connection of large capacities of offshore wind mainly in Denmark and Germany. To transmit this electricity deeper into continental Europe, internal grids in Germany must be strengthened. (ENTSO-E 2015a)

3.3 Summary of the European electricity grid

Efficient transmission grid with good connectivity and sufficient capacities is the greatest enabler in reaching climate and energy targets set by the European Union. Well-designed grid allows growing amounts of wind and solar power to be integrated without problem as a part of our energy system and thus reduce emissions. Isolated areas can be removed and interconnections reinforced to bring security of supply even to the most remote parts of the continent. Competitiveness can be reached by building an internal energy market that spans over all of Europe. Wholesale prices could be reduced significantly.

The current electricity grid is unfortunately not adequately equipped with either capacity or other technology to reach these benefits. Majority of the grid infrastructure is old and in desperate need of renewing. Many boundaries still exist both between and inside the member states. Some areas are even so isolated that they face great risk of total cut-off of electricity. Nine member states are lagging behind in reaching European Unions target of 10 % interconnection rate. Growing amounts of renewable production cannot be installed freely without risking system stability or even failure. The grid is also lacking technologies to efficiently monitor and control the complex system.

Smart grid technologies could alleviate these inadequacies. Remote metering and controlling used with advanced automation of the grid could provide tools to get control of the grid. Real time information would allow better monitoring of the condition of the grid. Automated systems can be used to bring supply security by automatically taking measures to prevent system failures or restore them. Controlling technologies could be used to provide load flexibility by limiting or shutting down consumption in compelling situations. Load profiles could be altered to better integrate renewables in the system. Leveling load peaks with electricity storages and controlling technologies would allow better optimization of the system and improve efficiency.

Increases in transmission capacities around Europe are still needed. Smart grid solutions can alleviate the pressure but growing demand and renewable production means that more and more electricity is flowing through the grid. Multi-billion investments are going to be made in the next decades for grid development projects. ENTSO-E is steering these by making plans and focusing resources on Projects of Common Interest that best address the problems in the current grid.

Investments are also needed in the Baltic Sea region. While some countries in the region are well connected a lot still remains to be done. Regional investment plan on the area identifies multiple pressing issues that need immediate actions. Growing renewable share and inadequate transmission capacity as well as energy surplus in the Nordics put pressure on the investments. A lot of grid improvement projects are commissioned in the last years to address these problems. Priority in the last years has been connecting the Baltic countries to the rest of the system.

The importance of improving transmission grid is unquestionable. Reaching the ambitious targets in GHG reductions, energy efficiency improvements and renewable share transmission grid plays a vital role. Building flexible and efficient system with smart grid technologies that can be easily modified to integrate many different types of production capacity is mandatory in creating secure, sustainable and competitive pan-European energy system.

4 The Baltic Sea region electricity market

The electricity grid is an important part of a functioning electricity market but other aspects of it need to be investigated as well. The grid is just a framework with which consumers, producers, power exchanges and other actors in the electricity sector are connected. In the following paragraphs other important parts of the electricity market regarding to this study are presented. Focusing on the Baltic Sea region the situation in the markets is investigated and some of the actors in the area are presented. Price formation in the day-ahead market and calculation process are examined. Finally production and consumption of electricity as well as other special qualities of each country in the region are evaluated.

4.1 Electricity markets and exchanges

The European Union is currently striving for the internal energy market. The market is still not integrated sufficiently from either physical or regulational perspective to reach this target. As a waypoint in reaching this single electricity market the European Regulators Group for Electricity and Gas launched Regional Initiatives to promote integration of the markets. These initiatives divided Europe to seven regional markets and thus advanced integration of the markets. The purpose of this is to increase co-operation between regulators, companies and other stakeholders and to transform from country-internal energy markets to regional markets. The Baltic Sea region consists of two of these regional markets, Baltic and Nordic. But since this division in 2006 a lot has changed. Integration of these regions has advanced so that the Baltic countries are not anymore that isolated. They are increasingly a solid part of Nordic region and will be considered as one in this study. (ERGEG 2006)

The European electricity market is based on electricity pools or exchanges. These exchanges act as mediators between the consumers and producers. The producers offer their products to be sold in the exchanges and consumers can purchase their electricity there. The sellers in the exchanges are energy companies with producing capacity. The buyers are either large energy consumers such as factories or companies with lots of facilities or electricity supply companies that supply the individual customers with the bought energy. This kind of market model creates high amount of competition and thus usually lower prices than for example bilateral trading. (Kirschen, Strbac 2004)

Bilateral trading, direct electricity trading between a producer and a consumer without a third party, still exists to some extent in the Baltic Sea region. This had been customary for a long time before the power exchanges started to claim the markets with better competition and prices. Some of the bilateral contracts are still valid but the majority of electricity is traded through an exchange. (Nord Pool 2004) For this reason bilateral trading is not considered in this study but all electricity is presumed to be traded through an exchange. This is also what the EU is trying to promote.

There are multiple power exchanges or power pools in Europe. Three different electricity exchanges operate in the Baltic Sea region. PolPX in Poland, EPEX in Germany and Nord Pool in Nordics and Baltics. Other European power exchanges are APX and N2EX operating in the UK, Belgium and the Netherlands and OMIE and GME in Southern Europe. Of the European power exchanges Nord Pool is the largest with over 500 TWh traded through the system. The simulations of this study are conducted using Nord Pool price calculation system. It gives credible data as the same system in used in majority of the region. Nord Pool system is in use also in PolPX. This system will be introduced more in detail later in this study. (Ruska, Similä 2011)

These exchanges do not act completely individually in their regions. The regional markets of the Europe and its many power exchanges are cooperating with each other. Projects like Price Coupling of the Regions (PCR) are a good example of that. Seven European power exchanges including Nord Pool have joined this common initiative to connect the exchanges and different regions. Common price calculation processes and algorithm, Euphemia, has been developed to harmonize electricity markets.

The system for price calculation used in this study, the Nord Pool system is based on Nordic electricity market design. This so-called Nordic market model consists of four components, seen in figure 12, all with distinctive purposes and different products to trade. These four parts are financial market, day-ahead market, intraday market and balancing market. First of the four, the financial market, is used to trade futures, forwards and options. In this market electricity is not traded physically but trading is done with contracts to for example buy electricity at a certain price in the future. These tools are used to manage risks related to electricity price by different participants in the market. Timespan of these contracts is up to six years. The financial market is not operated by Nord Pool power exchange but Nasdaq OMX. (Nord Pool 2015a)

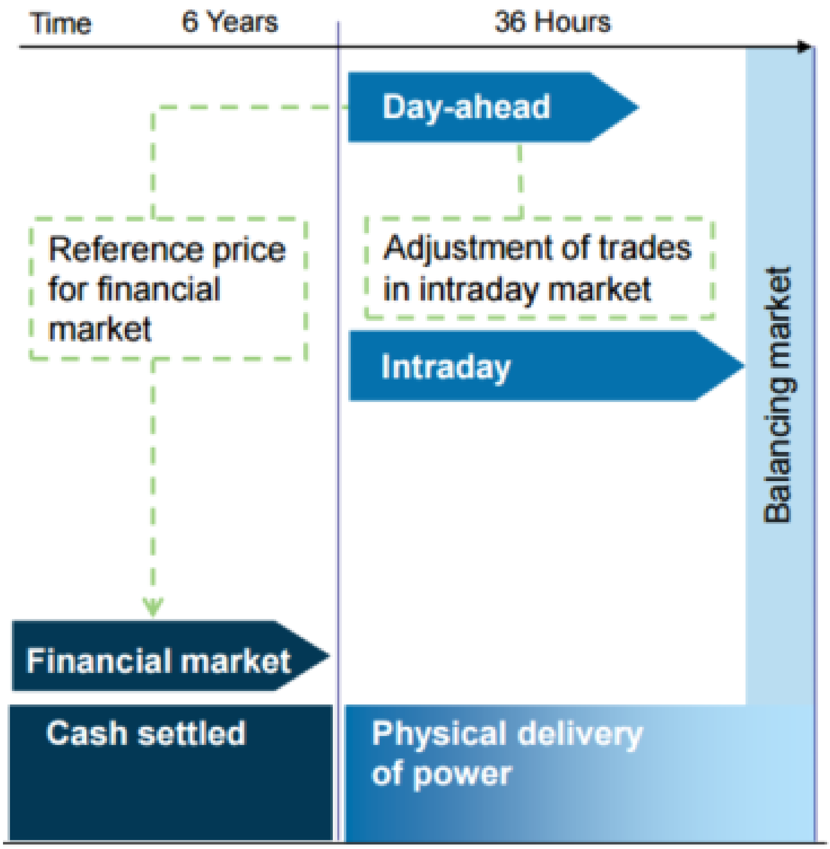


Figure 12: Different components of Nordic electricity market model. (Nord Pool 2015a)

When it comes to traded volume of electricity, the most important of the markets is the day-ahead market. Majority of physical electricity trade is done in the day-ahead market and that is why this market is simulated as a part of this thesis. This market also sets the reference price for the financial markets, as seen in figure 12. The day-ahead market works as an auction of power for the next day. This means that trades set today are delivered tomorrow. Producers and consumers input their either sell or buy orders which consist of volume and price amounts for each hour offered. Different kinds of offers can be made that include for example flexibility in amount and time of delivery. Market price is calculated based on the offers and some of them are accepted and some are not. The accepted ones are supposed to be delivered at accepted time the next day. Price formation in the day-ahead market will be presented in more detail in the next chapter. (Nord Pool 2015a)

In the day-ahead market the offers can be made up to 12 days before the actual date of delivery. This market gives the producers of electricity a possibility to plan the production well ahead. This is vital for conventional power production which is not very flexible in altering their power output. As results of the power auction are announced at 12:42 CET the previous day, the producers have time to adjust accordingly before the actual delivery. The consumers have the same advantage to plan ahead their demand for the next day. (Nord Pool 2015a)

The third part of the Nordic electricity market model, the intraday market, is as well as the day-ahead market a part of the physical electricity trading. Both of these markets are also operated by Nord Pool. The intraday market acts as a balancer to day-ahead market. This market operates continuously and the pace of trading and delivering is a lot faster. Trading happens only 30 minutes before the actual delivery. The producers and consumers make offers to buy or sell at a certain price and trading is done by first-come, first-served basis. The first sell order to fulfill the requirements of buy order is accepted and vice versa. (Nord Pool 2015a)

The intraday market is used in situations that are considerably less predictable than in the day-ahead market. These situations include for example unaccepted offers in the day-ahead market. If a producer fails to offer its capacity to consumer at a price that is accepted in the day-ahead auction and the production capacity cannot be adjusted, the producer can try to sell its available production capacity in the intraday market. Sometimes unpredictable failures in power plants result to situation in which a producer has offered to deliver power to customer for the next day but is unable to do that. Producer could try to buy the required capacity from the intraday market to be able to deliver the promised amount. As the situations that intraday market may be sudden and unpredictable, prices can also be more desirable than in the day-ahead market. That is why some market participants may try to leave part of the trading to be done on intraday market. Increase of renewables has also increased volumes in intraday markets as the production amounts can't be predicted very accurately. (Nord Pool 2015a)

The fourth and final component of the Nordic electricity market model is balancing markets. These markets are operated by the transmission system operators (TSOs) in the each country to adjust to sudden changes in the grid and maintain frequency. In these markets the production or consumption capacity is traded to balance the grid and keep it from failing. The TSO is always the other part of the trade along with one of the market participants. As little adjustment in the transmission system is needed at all times the TSOs require the producers or consumers that make the orders in the market to have easily and relatively quickly adjustable capacity. (Laine 2011) As seen in figure 12, the timespan between the set of the trade and delivery is the shortest of the four.

4.2 Price calculation and formation

In the following paragraphs the price formation in the day-ahead market of the Nordic market model will be presented. In the center of the price formation are the orders. These are offers of either supply or demand of electricity. Examples of the orders can be seen below in table 3. On the left is a sell order and on the right a buy order. Orders include minimum and maximum price limits. These set the area between which the prices can settle. The minimum price is -500€ and maximum price is 3000€. The same values are used in calculations for whole PCR area.

Table 3: Example of sell (left) and buy (right) orders.

Hour/Price	-500 €	32.20 €	32.30 €	3,000 €
00-01	0.0	0.0	-650.0	-650.0
01-02	0.0	0.0	-650.0	-650.0
02-02	0.0	0.0	-650.0	-650.0
03-04	0.0	0.0	-650.0	-650.0
04-05	0.0	0.0	-650.0	-650.0
05-06	0.0	0.0	-650.0	-650.0
06-07	0.0	0.0	-650.0	-650.0
07-08	0.0	0.0	-650.0	-650.0
08-09	0.0	0.0	-650.0	-650.0
09-10	0.0	0.0	-650.0	-650.0
10-11	0.0	0.0	-650.0	-650.0
11-12	0.0	0.0	-650.0	-650.0
12-13	0.0	0.0	-650.0	-650.0
13-14	0.0	0.0	-650.0	-650.0
14-15	0.0	0.0	-650.0	-650.0
15-16	0.0	0.0	-650.0	-650.0
16-17	0.0	0.0	-650.0	-650.0
17-18	0.0	0.0	-650.0	-650.0
18-19	0.0	0.0	-650.0	-650.0
19-20	0.0	0.0	-650.0	-650.0
20-21	0.0	0.0	-650.0	-650.0
21-22	0.0	0.0	-650.0	-650.0
22-23	0.0	0.0	-650.0	-650.0
23-24	0.0	0.0	-650.0	-650.0

Hour/Price	-500 €	3,000 €
00-01	179.0	179.0
01-02	175.4	175.4
02-02	170.9	170.9
03-04	169.3	169.3
04-05	171.7	171.7
05-06	184.5	184.5
06-07	195.1	195.1
07-08	202.0	202.0
08-09	206.3	206.3
09-10	208.7	208.7
10-11	189.5	189.5
11-12	210.6	210.6
12-13	209.0	209.0
13-14	207.3	207.3
14-15	204.8	204.8
15-16	204.8	204.8
16-17	204.3	204.3
17-18	202.8	202.8
18-19	203.6	203.6
19-20	203.5	203.5
20-21	198.8	198.8
21-22	199.9	199.9
22-23	197.3	197.3
23-24	187.1	187.1

Both orders contain volume values in megawatts for each hour of the day and for each price step. These orders are called single hourly orders in which a different value can be set on each hour. Other kind of order types exist as well in the Nord Pool system. With different timespans and flexibility options a lot of different tactics can be used to make the orders. However, single hourly orders are the only ones used in this thesis so understanding how they work is enough. (Nord Pool 2016)

On the left in table 3 is an example of sell order of for example a large coal fired power plant. The sell values are presented as negative in this system. The volume value of 650MW is the same throughout the day which is typical for conventional power production unit. From the four price steps, -500, 32.2, 32.3 and 3000 we can see that this order is price dependent. It means that the price of electricity affects on the realization of this order. When the price is under 32.2, electricity will not be produced. Between 32.2 and

32.2 the volume can be interpolated to be between 0 and 650 MW. If the price is over 32.3 full 650 MW will be produced.

On the right side of the table is then an example of buy order. As can be seen, the volume values are now varying. The volume values follow approximately the hourly demand variation in figure 7 of the chapter 3. This example buy order could be from a small local retail company. In this order there are only two price steps. This means that this order is price independent order. The buyer is ready to purchase the amount of electricity shown in the order regardless of the price.

In the process of making the offers for day-ahead market the producers and consumers of electricity must price the electricity that they are either selling or buying. In the European electricity market the producers tend to price the electricity that they are selling according to the short term marginal cost of the production method. (Borenstein 2000) That is the cost of an additional unit of electricity produced. In the sell order in table three, this marginal cost of that production method is 32.2€. This leads to the situation shown in figure 13. The merit order is the order in which the production methods are taken into use if demand grows.

In the figure we can see that production method with lowest marginal cost is hydro power. Solar and wind power that are not shown in this picture have marginal costs around the level of hydro power. These methods are used first to meet the demand. Nuclear power and CHP follow that. In the figure 13 consumption level is so high that a part of production capacity of the coal condensing power plants must be taken into use. In this situation the market price of the electricity is set by the highest marginal cost of the production methods in use. In this case it is coal condensing power. If the consumption was to increase oil condensing power had to be used to meet the demand, and market price would climb even higher.

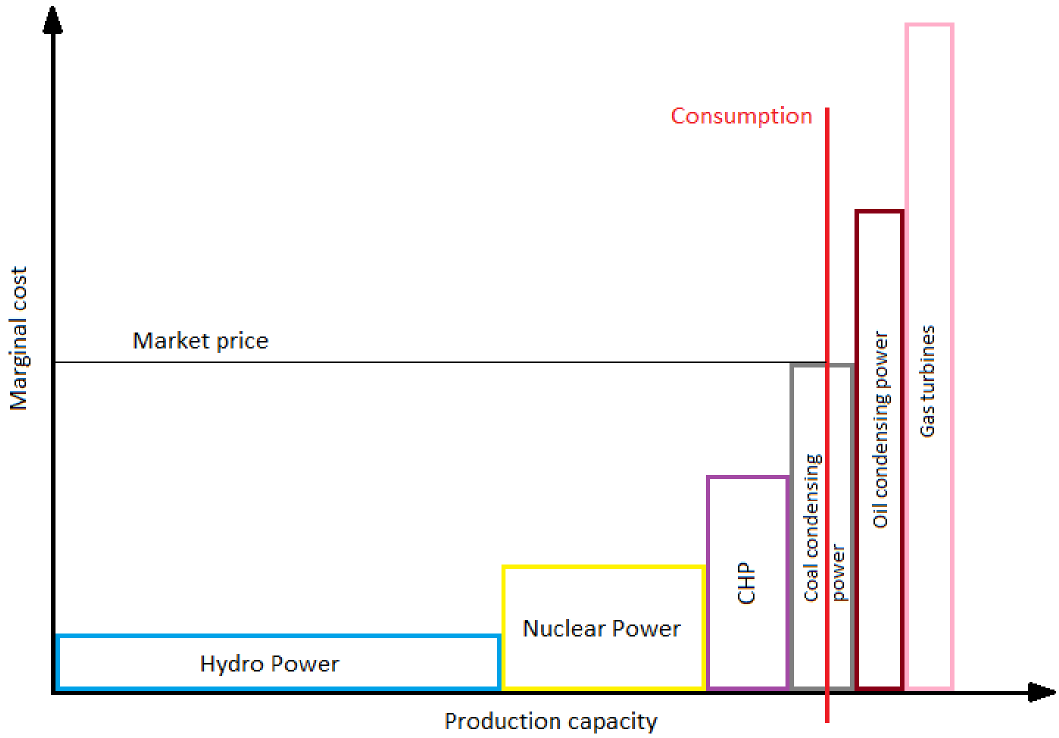


Figure 13: Merit order of production.

Demand side pricing depends highly on the purpose of the demand. Some buyers of electricity need the electricity regardless of the price and the order is made price independent as in table 3. For other customers buying the electricity is not mandatory. For them the electricity price might rise higher than the cost of not using the electricity. In these cases price dependency exists. If the consumption of the electricity rises and more and more expensive production methods are taken into use the most price dependent consumers will reduce consumption.

Every market participant that wants to participate in trading in the day-ahead market has to submit their orders by 12:00 CET the previous day. After the orders have been submitted the price calculation takes place. The purpose of calculation is to find equilibrium between supply and demand. This is done by aggregating data from all buy and sell orders and creating single supply and demand curves. The point in which these curves intersect tells us the market price of electricity. Individual prices are calculated for each hour of the day. If the supply and demand curves do not intersect for some hour, one of the curves is cut to make them intersect. (Nord Pool 2014)

The price calculated in this simple way using only buy and sell orders is called the system price. It is the price that is calculated assuming that all transmission capacities between areas are infinite. This is however not the case in real life. System price is used as a reference price in financial markets but not in physical trading of electricity. To calculate the "real" price of electricity capacities are needed. TSOs submit the present transmission capacities for the next day before the calculation. Taking into account the constraints in transmission capacity individual prices for each area can be calculated. This price is called Area price and it is used in settlement in the area that it concerns. By having variation in prices, higher prices in areas with less power, the flow of power is ensured to go towards the area with power deficit. (Nord Pool 2014)

Algorithm called Euphemia or EU Pan-European Hybrid Electricity Market Integration Algorithm is used to perform these calculations for all PCR areas. It is created to find most competitive price of the possible solutions and allocate transmission capacity efficiently thus maximizing socio-economic benefits of the calculation solution. Euphemia needs three kinds of input data to succeed in the calculation process. It needs of course the orders from each bidding area and network data that consists of capacities, losses, tariffs and constraints. In addition to these it also requires topology of the network, how the bidding areas are connected and how the network is built between them. (EPEX spot et al. 2015)

This data is collected from all areas of all electricity exchanges joined in the PCR project so the mathematical problem to be solved is quite complex. The Euphemia uses combinatorial optimization to solve this problem. It is based on modelling the market problem with an aim to find the intersection of the supply and demand curves that maximizes socio-economic welfare. The Euphemia algorithm also has three sub problems that further search for the most feasible solution. (EPEX spot et al. 2015)

4.3 Situation in the Baltic Sea region countries

The Baltic Sea region consists of nine countries and altogether 17 bidding areas. These countries differ a lot when it comes to electricity production and consumption. The volumes vary a lot but there are differences also in production methods. In this chapter the special qualities of the energy sector in each country in the Baltic Sea region are presented. Production mixes will be investigated as they have an important role in the calculation and price formation process. Relative amounts of installed capacity for each country in the Baltic Sea area can be seen in figure 14 below. In this figure the production methods are divided to nine types based on the fuel source used. This division is also used in the simulation part of this study.

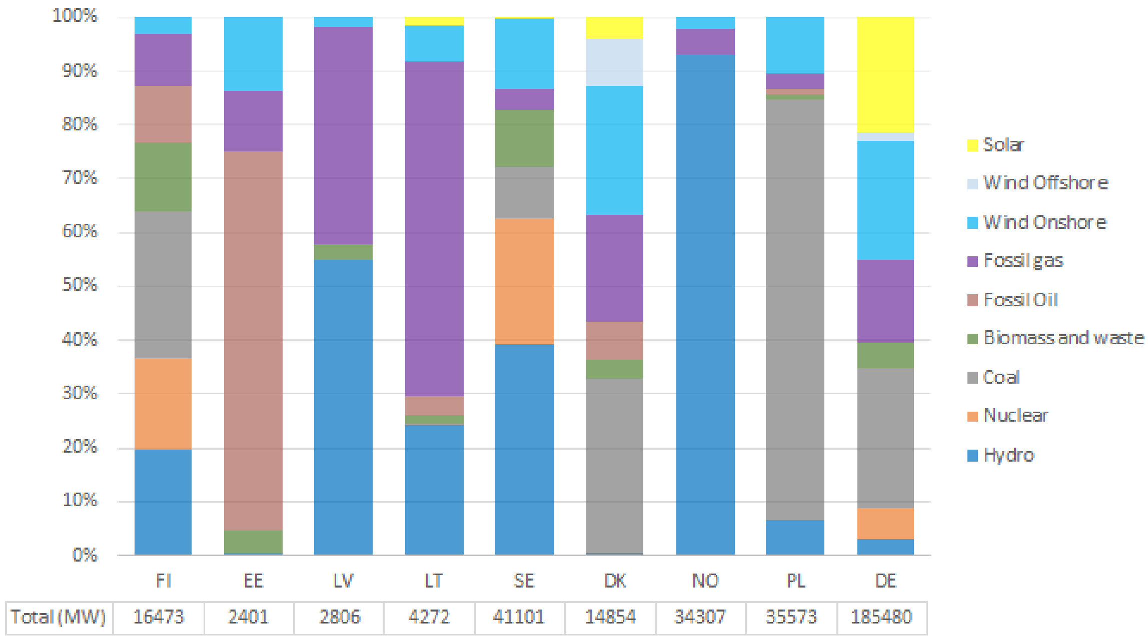


Figure 14: Installed production capacities in Baltic Sea region in 2015. (ENTSO-E 2015c)

4.3.1 Norway

Norway holds a great deal of Europe's energy resources. Despite of Norway's huge oil and gas resources, the country is a strong advocate for climate change mitigation. Norway's energy resources do not end with oil and gas but it also has a huge potential of hydropower. Over 90 % of Norway's installed production capacity is hydropower and practically all electricity is made with that. Some gas capacity exists for emergency situations. Demand amounts to about 130 TWh yearly and is growing at a steady pace as all over Europe. As hydropower can be relatively easily stored by pumping water in to reservoirs Norway also possesses a relatively large capacity of electricity storages. (IEA 2011b)

Norway is an important resource of electricity also for other countries in the Baltic Sea region. The country generates more electricity than it consumes and thus is a net exporter especially during wet years with a lot of rainfall. Cheap hydropower reduces average prices all over the region and dispatchability of production also helps balance the system. On the other hand during the very dry years Norway has to import some of its electricity because of the lack of base load capacity. (IEA 2011b)

4.3.2 Sweden

Sweden, as well as Norway utilizes its abundant hydropower source. Mountainous regions in Northern Sweden provide installed hydropower capacity that covers almost 40% of the whole production capacity in the country. What is exceptional in Sweden is it's nearly carbon free production capacity. Only about 15% of Sweden's installed capacity is based on conventional fossil fuels. Instead of fossil fuels, Sweden has large capacities of nuclear and biomass production. As Sweden might decommission its nuclear capacity, biomass and other renewables are supposed to fill the needed production capacity. (IEA 2013d)

Sweden's import and export is highly dependent on the water reservoirs. As in Norway the heavy rains make Sweden an exporter of electricity mainly to continental Europe. In the cold and dry winters the electricity flows are opposite. Electricity from thermal power plants flow from the continent to Sweden. Electricity demand is at the same level with Norway, about 150 TWh. The demand has stayed on this stable level since 1990s. (IEA 2013d)

4.3.3 Finland

Finland has the highest energy consumption per capita in the Europe. This is due to energy intensive industries which thrive in Finland, almost 50% of the consumption is from industry. Also location in the North next to a big continent makes weather colder than in other parts of the Baltic Sea area. Regardless of high intensity of electricity consumption per capita, Finland has only about 80-90 TWh of yearly demand. What is exceptional in the Finnish electricity system is that production is about 10% less than demand. This means that Finland needs to import large amounts of its electricity. The deficit is due to decommissioning of infeasible power plants in the low market prices. (IEA 2013b)

Production mix in Finland is quite diverse. Big shares, near 20%, of coal, hydro and nuclear and little smaller shares of biomass, gas and oil is used for electricity production. From the shares in figure 14 we can tell that a lot of Finland's installed capacity is run by fossil fuels. Finland is very highly dependent in importing both electricity and fuels to produce it. Majority of electricity needed in Finland is imported from Russia and Sweden. (IEA 2013b)

4.3.4 Denmark

Smallest of the Nordic countries with only 30 TWh yearly demand, Denmark is the forerunner in wind electricity production in the whole Europe. This has been boosted by location between Baltic and Northern Seas and thus an ample source of wind. Also decent amount of almost 5% solar capacity exists. Denmark is also expected to grow its variable renewable production in the future. To balance out the variations in production created by wind speed changes, Denmark needs alternative supply that can be put to use quickly. That is why Denmark has a relatively large share of production capacity using fossil gas. Also big share of 33% fossil coal production exists to provide base load. (IEA 2011a)

Due to high renewable share and interconnection rate, Denmark is highly dependent on other countries. Balancing is needed because of high renewable production share. A lot of transmission capacity exists also because Denmark acts as a transit country between the Nordics and continental Europe. For these reasons import and export levels vary a lot between the years. (IEA 2011a)

4.3.5 Estonia

Estonia is highly dependent on single source of electricity production, fossil oil, which covers almost 80 % of installed capacity. This is because of Estonia's large domestic oil shale resource. In the recent years Estonia has also increased its renewable production capacity. Majority of these increases come from wind and biomass production. Some fossil gas capacity exists to handle peak load situations. Demand on Estonia and also other

Baltic countries is small compared to Nordics. Estonia consumes only 7-8 TWh yearly but the growth has been faster in the recent years compared to other European countries. (IEA 2013a)

As production in Estonia is higher than demand, the country is net exporter of electricity. Estonia exports almost 30% of its production yearly mainly to Finland, Latvia and Lithuania. In the recent years both imports and exports have grown because Baltics joined Nord Pool electricity market. Estonia acts as a transit country between the Nordics and other Baltic states. (IEA 2013a)

4.3.6 Latvia

Latvia has the largest share of renewables in its production mix of the Baltic countries. Over 50% of the production capacity is renewable. The majority of this capacity is hydropower. The rest of the production capacity is fossil gas based with an exception of small wind power share. In contrast to Estonia, Latvia imports a great deal of its electricity. Of the 8 TWh consumed yearly, only approximately 80% of the electricity is produced domestically. The rest is imported mainly from Estonia and Russia. (European Commission 2014c)

4.3.7 Lithuania

Main source of production in Lithuania is fossil gas which adds up to over 60% of the total production capacity. As the country is, as well as Latvia, in the path of main Russian gas lines to Europe the natural gas resource is abundant. Recent decommissioning of an old nuclear power plant has further increased the production capacity of fossil gas. This event had a major effect in Lithuania's energy sector. The country went from producing almost 70% of its electricity from nuclear sources to zero. To satisfy the need of almost 10 TWh yearly demand imports are needed. Today Lithuania gets more than half of its electricity from the neighbouring countries, mainly Russia. (European Commission 2014d)

4.3.8 Poland

Poland has a large domestic supply of fossil coal. This is the reason why biggest share in production capacities in Poland is coal. It covers 80 % of all production capacity. Renewables exist only in small shares of wind and hydropower. Demand of electricity is at the same level as in Nordic countries, approximately 120 TWh. Poland's production capacity is relatively old compared to other countries in the Baltic Sea area. Over 60 % of production capacity is over 30 years old. This means that Poland's production capacity is declining unless investments are made. Plans exist to stop this decline by nuclear power in the following decades. (IEA 2011c)

4.3.9 Germany

Germany is the largest consumer and supplier of electricity of Europe and of course the Baltic Sea region. With over almost 200 GW of installed electricity production capacity Germany exceeds production capacity of the rest of the region. Demand of electricity is high in Germany as well. As well as many other countries in the region Germany is also highly industrialized. Electricity consumption is also highest in the region with over 500 TWh yearly. (IEA 2013c)

Shutting down almost all nuclear power plants in the recent years has revolutionized Germany's energy sector. Huge investments in the renewable energy production have been made since and the country still keeps on being the powerhouse Europe's solar production. As can be seen from figure 14 the production capacity of nuclear power is relatively small less than 10%. Solar and wind power on the other hand have risen to fill this deficit of power. Today solar and off- and onshore wind power make up to more than 40% of all installed production capacity in Germany. (IEA 2013c)

Imports of electricity have also grown since decommissioning of nuclear capacity. Germany had been for years a net exporter of electricity. However, the lack of steady base load and moving towards more variable production capacity has increased imports a lot. More and more electricity is today imported from Denmark, Sweden and other neighboring countries, especially in unfavorable weather conditions. (IEA 2013c)

5 Market simulation

Simulations were performed to gain better understanding on how the European energy strategies affect the electricity system in the Baltic Sea area. The goal was to put in numbers how the changes will transform the energy system, its prices and transmission volumes. The simulation would also give answers on how adequate are the grid improvement plans to handle policy changes and how would the production sources be used in the future. This chapter describes the market simulations conducted as a part of this study. First the background of the simulations and scenarios are described. Then the parameters used in the simulation and how they were chosen are presented. Finally the whole simulation process is described in detail.

The Nord Pool test system was used to run these simulations. The system includes a back-end interface used to configure the parameters that are described in the following chapters. In addition in this simulation a PCR calculation server, similar to one that is used in actual price calculation in Nord Pool market area, was used to calculate the system and area prices. Also electricity flows are determined in the PCR calculation. The principle behind the price calculation and formation is explained in detail in chapter four of this study. As a result from the calculation hourly prices, flows and production amount values are saved in the back-end system.

The back-end of the test system was used to configure the areas, connections between them and the transmission capacities. The buy and sell bids for each scenario were inserted through the back-end. The back-end system creates the buy and sell curve files in addition with area configuration file that are then used in the PCR calculation server to run the calculation. The process of the simulation is more closely described in the end of this chapter.

For this simulation four years were chosen to investigate the electricity system. Obviously these are the 2015, 2020, 2030 and 2050. The present (2015) scenario acts as a baseline to compare the other results against. The three future scenarios 2020, 2030 and 2050 represent the progress of the implementation of the European Energy strategies. These three time periods were a natural choice as they are the most important milestones of the EU energy strategies. The scenarios are compiled from various different sources and they try to represent the most probable direction of development during the next decades. Different simulations were run for a typical winter and a summer day, respectively. The sensitivity and security of the system is also tested by creating simulations with low renewable production values.

These simulations have of course some inaccuracies as the system must be simplified to some extent for these simulations to work. Accurate predictions are impossible to make that far to the future and some assumptions must be made. Having multiple sources of simulation data is crucial to create the most accurate simulation possible. Another thing that causes inaccuracies especially in the later time periods are electricity storage and demand flexibility. These two possibly very effective means to balance the energy system are left out of the scope of this study for two reasons. They are very hard to simulate as both of them are yet in very early stage of development at least in the large scale. As they are not yet well implemented in the energy system, the effect they might have is rather small in the 2020 and 2030 scenarios. In 2050, a bigger effect could be possible but it is impossible to predict the scale of it. The production mixes needed also to be simplified and smallest production units were not taken into account.

Although some inaccuracies may occur in this simulation, it still shows important issues that the energy system might face over the following decades. Inadequacies of the grid will be easily detected and the price development can be predicted. With these the direction of the development and the performance of the system can be assessed as the EU strategies are implemented.

5.1 Simulation data

In these chapters the collected data for the simulation is presented. This data includes demand, production, capacities and connections. The data was collected from mainly historical data from 2015 to create the baseline for this simulation. Predictions for the future were made mainly using EU strategy papers but comparison to various other sources were made to ensure more accurate data. The actual bids, capacities and other documents for the simulation system were compiled based on this data.

5.1.1 Demand

In nearly all of the scenarios and predictions that consider the world energy sector, the demand of electricity is expected to grow. The growth is of course fastest in the developing countries but some increase can be found everywhere. In the developed countries such as the ones in this study the increase is mostly driven by technological development. More and more electrical appliances and solutions are taken into use. One example of this is electrical vehicles that could increase the demand radically. However, as the increase of electricity in final energy consumption increases, so increases the efficiency as well. This slows down but does not totally eliminate the increase in consumption in the most developed countries. (Alanen et al. 2009) (European Commission 2011a)

For this study it is reasonable to focus on the EU area and other developed areas when considering the rate that the demand is increasing. All Baltic Sea area countries are relatively developed and follow the EU policies in developing their energy system. This steers also their consumption development. In these highly industrialised countries the demand is expected to grow throughout the scope of this study.

The baseline for the demand level was set by studying historical demand data in the Baltic Sea area. The year that was selected to act as a baseline in this study was 2015. The data was collected from the Nord Pool website for the Nordics and the Baltics. Demand data for Germany and Poland was however not available there as they are not a part of Nord Pool day ahead market. Demand data for these countries was collected from ENTSO-E. The Nord Pool demand data was also compared against the ENTSO-E data to verify it. The data collected was hourly data so that each hour of the year had a different value.

This simulation consists both winter and summer scenarios for each time period. This is because the demand varies a lot between winter and summer due to radical temperature changes especially in the Nordics. The difference between winter and summer demand can be seen in figure 15. From the data an average summer and winter demand days for each bidding area were combined. This was done by calculating the hourly average values over three months for all the areas. Summer months were June, July and August and winter months December, January and February.

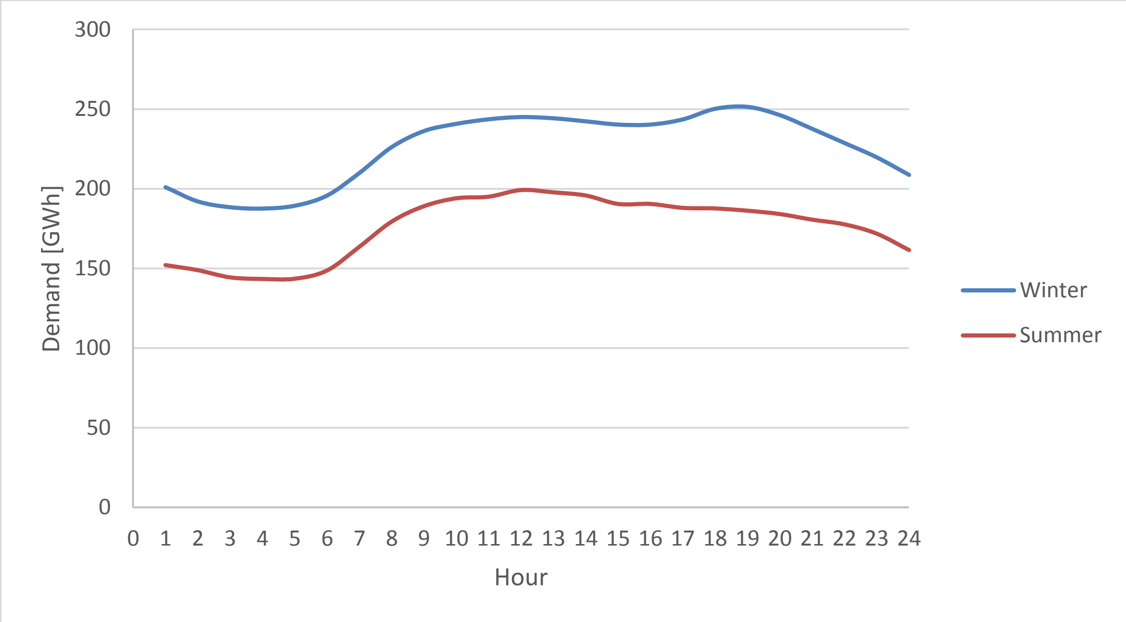


Figure 15: Aggregated demand in the Baltic Sea area 2015. (Nord Pool 2015b) (ENTSO-E 2015b)

The load profiles for the winter and summer days were rather similar. The second demand peak in the evening is not that visible in the summer but otherwise the profiles are very close to each other. The differences are more visible in the level of demand. In winter the demand levels are approximately 50 GWh bigger in the winter throughout the day. This rather significant difference is due to lower temperatures in the Baltic Sea area.

The baseline of demand was set for each bidding area separately based on the hourly demand data. Using these average winter and summer days' predictions were made for the different time periods. To simplify the process a similar growth was assumed to take place in all countries in the area. The growth rate of the demand was then assessed using various sources. Demand is expected to grow relatively steadily in the EU area until the year 2050. (European Commission 2011a).

As demand growth is expected to be steady and all areas to have similar growth a single yearly growth rate for the whole period was selected. Using growth predictions and demand development assessments from Nordic, EU and world level a yearly growth rate of one percent was selected. (Alanen et al. 2009) (European Commission 2011a) (VTT 2009) (IEA 2015) (EIA 2015c) Using this yearly growth rate the calculations were done to create average winter and summer days for 2020, 2030 and 2050 for each bidding area in the Baltic Sea region.

5.1.2 Production

Production parameters are a bit more complicated to set. Unlike demand, which is considered in this study as a whole in all countries, different production types must be taken into account when assessing production. Different production types will develop very differently during the time period in this study. However the overall production capacity will grow as consumption and the share of variable renewables increase. This is the case even if some production types might face reductions in capacity. The production capacities for all areas and scenarios can be seen in tables four and five.

In this study the production capacity is divided into nine different production types. This division has been done based on fuel type used because fuel costs affect the most on the cost of production. As can be seen in figure 14 in chapter 4 the production types are: onshore wind, offshore wind, solar, biomass and waste, coal, oil, gas, nuclear and hydro. These all will be handled separately as the principles of production differ a lot from each other. Production with gas and oil is flexible but production with wind or solar depend only on resource availability which changes seasonally. Also individual marginal costs of the production types affect their utilization. These differences will be introduced more in detail later in this study.

The baseline for production capacities had to be made before making predictions into the future. This baseline was set using again historical data. Rather than having hourly values of actual production amounts only capacities of each production method in each bidding area were needed. This data was extracted from ENTSO-E transparency platform and the relative amounts are shown in figure 14 in chapter 4 of this study. The original data included various production types but in order to simplify production simulation they were grouped so that different types of coal are considered as one. This data lacked also the smallest production units. That is why solar and wind capacities were zero in nearly all of the areas. Solar and wind will play some part in the future and this is why small initial capacities of solar and wind power were added. (ENTSO-E 2015c)

The EU policies drive the Baltic Sea region countries towards bigger and bigger shares of renewable production capacities. As can be seen from figure 14 in chapter 4 all countries have a lot to do to develop their production mix. Development of the production capacities was estimated using EU growth forecasts and comparing those to other sources to verify their correctness. As the countries are quite similar the same growth rates are again expected for all areas. As some areas did not have any initial capacity of for example nuclear power, new capacity was not expected to appear apart from solar and wind capacity as explained earlier.

Table 4: Production capacities in Nordic countries in MW.

Scenario	Country	Wind On	Wind Off	Hydro	Oil	Biomass	Gas	Nuclear	Coal	Solar
2015 Summer	FI	136	5	1126	1705	2123	1611	2752	4522	1
2015 Winter		173	6	1242	1705	2123	1611	2752	4522	1
2020 Summer		182	9	1144	1905	2529	1666	2809	4347	2
2020 Winter		228	11	1262	1905	2529	1666	2809	4347	1
2020 Low Renewable		114	5	1262	1905	2529	1666	2809	4347	0
2030 Summer		300	28	1181	2377	3589	1782	2926	4016	6
2030 Winter		370	33	1303	2377	3589	1782	2926	4016	3
2030 Low Renewable		185	17	1303	2377	3589	1782	2926	4016	0
2050 Summer		692	232	1257	3702	7230	2038	3174	3429	49
2050 Winter		853	279	1387	3702	7230	2038	3174	3429	31
2050 Low Renewable		426	139	1387	3702	7230	2038	3174	3429	0
2015 Summer	DK	977	411	3	1051	560	2941	0	4847	132
2015 Winter		1246	507	3	1051	560	2941	0	4847	64
2020 Summer		1314	754	3	1174	667	3042	0	4659	230
2020 Winter		1646	917	3	1174	667	3042	0	4659	112
2020 Low Renewable		823	458	3	1174	667	3042	0	4659	0
2030 Summer		2162	2340	3	1465	947	3253	0	4305	699
2030 Winter		2666	2813	4	1465	947	3253	0	4305	339
2030 Low Renewable		1333	1406	4	1465	947	3253	0	4305	0
2050 Summer		4985	19651	3	2282	1907	3721	0	3675	5928
2050 Winter		6146	23616	4	2282	1907	3721	0	3675	3760
2050 Low Renewable		3073	11808	4	2282	1907	3721	0	3675	0
2015 Summer	NO	207	8	11019	0	0	1610	0	0	3
2015 Winter		265	10	12158	0	0	1610	0	0	2
2020 Summer		279	15	11194	0	0	1665	0	0	6
2020 Winter		349	18	12351	0	0	1665	0	0	3
2020 Low Renewable		175	9	12351	0	0	1665	0	0	0
2030 Summer		459	46	11552	0	0	1781	0	0	17
2030 Winter		566	55	12746	0	0	1781	0	0	8
2030 Low Renewable		283	28	12746	0	0	1781	0	0	0
2050 Summer		1059	387	12304	0	0	2037	0	0	148
2050 Winter		1305	465	13576	0	0	2037	0	0	94
2050 Low Renewable		653	232	13576	0	0	2037	0	0	0
2015 Summer	SE	1481	6	5573	0	4381	1557	9528	3981	19
2015 Winter		1890	8	6150	0	4381	1557	9528	3981	9
2020 Summer		1992	12	5662	0	5219	1610	9724	3827	34
2020 Winter		2496	14	6247	0	5219	1610	9724	3827	16
2020 Low Renewable		1248	7	6247	0	5219	1610	9724	3827	0
2030 Summer		3279	37	5843	0	7407	1722	10129	3536	102
2030 Winter		4043	44	6447	0	7407	1722	10129	3536	50
2030 Low Renewable		2021	22	6447	0	7407	1722	10129	3536	0
2050 Summer		7560	309	6223	0	14920	1970	10990	3018	868
2050 Winter		9321	372	6867	0	14920	1970	10990	3018	551
2050 Low Renewable		4661	186	6867	0	14920	1970	10990	3018	0

Table 5: Production capacities in Baltic countries, Poland and Germany in MW

Scenario	Country	Wind On	Wind Off	Hydro	Oil	Biomass	Gas	Nuclear	Coal	Solar
2015 Summer	DE	11204	902	1925	0	8860	28540	10790	48230	8734
2015 Winter		14292	1112	2124	0	8860	28540	10790	48230	4235
2020 Summer		15069	1654	1956	0	10555	29516	11012	46360	15218
2020 Winter		18874	2012	2158	0	10555	29516	11012	46360	7376
2020 Low Renewable		9437	1006	2158	0	10555	29516	11012	46360	0
2030 Summer		24798	5138	2018	0	14980	31568	11471	42835	46190
2030 Winter		30575	6174	2227	0	14980	31568	11471	42835	22398
2030 Low Renewable		15288	3087	2227	0	14980	31568	11471	42835	0
2050 Summer		57172	43136	2150	0	30173	36112	12446	36568	391555
2050 Winter		70492	51840	2372	0	30173	36112	12446	36568	248406
2050 Low Renewable		35246	25920	2372	0	30173	36112	12446	36568	0
2015 Summer	EE	90	2	3	1698	100	267	0	0	1
2015 Winter		114	2	3	1698	100	267	0	0	0
2020 Summer		121	3	3	1897	119	276	0	0	1
2020 Winter		151	4	3	1897	119	276	0	0	1
2020 Low Renewable		76	2	3	1897	119	276	0	0	0
2030 Summer		198	9	3	2367	169	295	0	0	3
2030 Winter		245	11	3	2367	169	295	0	0	2
2030 Low Renewable		122	6	3	2367	169	295	0	0	0
2050 Summer		457	77	3	3687	341	338	0	0	30
2050 Winter		564	93	3	3687	341	338	0	0	19
2050 Low Renewable		282	46	3	3687	341	338	0	0	0
2015 Summer	LT	77	2	355	160	60	2651	0	23	15
2015 Winter		98	2	391	160	60	2651	0	23	7
2020 Summer		104	3	360	179	71	2742	0	22	26
2020 Winter		130	4	398	179	71	2742	0	22	13
2020 Low Renewable		65	2	398	179	71	2742	0	22	0
2030 Summer		171	9	372	223	101	2932	0	20	79
2030 Winter		210	11	410	223	101	2932	0	20	38
2030 Low Renewable		105	6	410	223	101	2932	0	20	0
2050 Summer		393	77	396	347	204	3354	0	17	671
2050 Winter		485	93	437	347	204	3354	0	17	425
2050 Low Renewable		242	46	437	347	204	3354	0	17	0
2015 Summer	LV	14	2	530	0	82	1136	0	0	1
2015 Winter		18	2	585	0	82	1136	0	0	0
2020 Summer		19	3	539	0	98	1175	0	0	1
2020 Winter		23	4	594	0	98	1175	0	0	1
2020 Low Renewable		12	2	594	0	98	1175	0	0	0
2030 Summer		31	9	556	0	139	1257	0	0	3
2030 Winter		38	11	613	0	139	1257	0	0	2
2030 Low Renewable		19	6	613	0	139	1257	0	0	0
2050 Summer		71	77	592	0	279	1437	0	0	30
2050 Winter		88	93	653	0	279	1437	0	0	19
2050 Low Renewable		44	46	653	0	279	1437	0	0	0
2015 Summer	PL	1027	3	795	345	375	984	0	27793	3
2015 Winter		1310	4	877	345	375	984	0	27793	1
2020 Summer		1382	6	808	385	447	1018	0	26715	5
2020 Winter		1730	7	891	385	447	1018	0	26715	3
2020 Low Renewable		865	4	891	385	447	1018	0	26715	0
2030 Summer		2273	18	833	481	634	1088	0	24684	16
2030 Winter		2803	22	920	481	634	1088	0	24684	8
2030 Low Renewable		1402	11	920	481	634	1088	0	24684	0
2050 Summer		5242	155	888	749	1277	1245	0	21072	138
2050 Winter		6463	186	979	749	1277	1245	0	21072	88
2050 Low Renewable		3231	93	979	749	1277	1245	0	21072	0

The annual growth rates of generation capacity were selected for each production method. The selected values are shown in table six. These values represent the reference scenario in the EU 2050 energy roadmap. These values were selected after comparing them with other growth forecasts. Wind power is expected to grow a lot all over the EU and also the rest of the world. Annual growth rates between 5 and 10 percent were expected. Offshore wind will grow at a greater pace because of better wind speeds available. Solar power will continue its fast growth especially in the southern part of the Baltic Sea region. Hydro power is highly utilized in the Baltic Sea region so very slow development is expected. (European Commission 2011a) (VTT 2009) (EWEA 2012) (ENTSO-E 2014)

Fossil fuels are predicted to start having negative growth rates nearing the year 2050. However, as seen in table six, only coal has a negative value. Fast growth of variable energy sources, wind and solar, increase the need of power plants that are able to follow the variating production patterns. This means mainly quickly dispatchable generation capacity, usually gas- or oil-fired. This is why these two production types have positive annual growth rates. Good growth can be noticed also in biomass capacity which is utilized a lot in the Nordics. This will replace the decreasing coal-fired capacity. (ENTSO-E 2014) (European Commission 2011a) (VTT 2009)

Table 6: Annual growth rates of generation capacity selected for this simulation.

Wind On	Wind Off	Hydro	Fossil Oil	Biomass	Fossil gas	Nuclear	Coal	Solar
4,27 %	11,23 %	0,32 %	2,24 %	3,56 %	0,67 %	0,41 %	-0,79 %	10,39 %

Annual growth rates are of course not the ideal way to simulate development of production methods especially in a short period of time. A single large power plant investment can change capacity by several percent during one year. However with longer time periods the simulation of these growth rates will represent the development with adequate accuracy. Annual growth rates work also best when modelling development of small production units that are constantly put into operation.

5.1.3 Capacity factors

Generation capacity itself cannot be used to simulate power production because all built capacity cannot be used all the time. Capacity factors that provide the share of electricity that can actually be produced over a period of time are needed. Capacity factors of these production methods differ a lot. While some have almost the same capacity factor throughout the year, some capacity factors change seasonally and even daily.

To avoid unnecessary complexity, biomass, fossil oil, fossil gas, coal and nuclear power plants are assumed to have maximum capacity factors of 100% over the average winter and summer days. This means that these power plants are able to produce at a maximal power if needed. In reality the capacity factors are not nearly this big. Depending on the role of the power plant, fuel and electricity costs, capacity factors for conventional power plants are usually between 50-80%. For nuclear power plants this figure is around 90%. (EIA 2015a)

Unlike conventional power production which is not affected by weather or seasonal variations, those renewables that depend on resources such as wind, sun and water have radical variations in their capacity factors. These production types are listed in table 7. The capacity factor values are extracted from U.S. Energy Information Association (EIA)

Electric power monthly statistics. The values were then corrected to represent the situation in the Baltic Sea region. Wind and hydro values proved to be reasonable when compared to European sources so they were used as they were. Solar values were noticeably higher in the EIA statistic compared to values representing Northern Europe. While EIA values were 20-30% corresponding values for Northern Europe were 10-20%. These values were adjusted to follow more closely the situation in the Baltic Sea region. Monthly values can be seen in table 7. Averaged capacity factor values from winter and summer months were used to create production data for the simulation.

Power production with hydropower varies seasonally. In table 7 can be seen that capacity factor is highest in the winter. This is however not a normal situation. These values are from 2015 which was an unconventional year regarding hydro power production. Usually the peak in capacity factor in the Nordics occur in the spring and early summer when snow melts after the winter. The values in the table 7 were still used in this simulation. This makes the production amounts slightly too high in the winter and low in the summer which doesn't represent fully the normal situation. Differences to the normal situation are not however very big and this difference will not have notable effect on the simulation results.

Table 7: Capacity factors for different production types. (EIA 2015a) (Open Energy Information 2015) (Boccard, N. 2009) (Eurelectric 2009) (EWEA 2009) (IRENA 2015)

Month	Wind Onshore	Wind Offshore	Hydro	Solar
Jan	31.7	36.7	41.5	7.7
Feb	34.4	39.4	42.5	14.2
Mar	31.7	36.7	41.8	18.5
Apr	37.8	42.8	39.3	22.3
May	35.2	40.2	34.1	22.0
Jun	28.3	33.3	35.0	22.4
Jul	27.7	32.7	35.5	21.9
Aug	26.0	31.0	33.0	21.7
Sep	28.2	33.2	28.4	17.2
Oct	31.9	36.9	28.1	13.5
Nov	39.1	44.1	33.4	11.5
Dec	38.5	43.5	30.2	10.1

Wind power production is also affected by seasonal changes as wind speeds determine the production amounts. Table 7 shows that wind power production has highest capacity factors in the spring and late autumn. Wind speeds are most optimal for electricity production during those times. Solar power has relatively low capacity factors compared to others production methods. It varies a lot depending on the time of the year with lowest values in the winter when sun doesn't rise that much above the horizon. Summer months have the highest capacity factors.

Both wind and solar power production have also variations in shorter time periods than seasonal variations. Both these production types vary also during the day. Solar power has the biggest variations. Production stops totally as the sun goes down and doesn't start until the sun rises again. Differences between production during the night and day are large. This has been taken into account in this simulation. With solar power factors changing between 0 in the night and rising gradually to 1 during the day using normal distribution and considering shorter day during winter.. This distribution model is not optimal to model solar radiation but is accurate enough for this kind of study. (Badescu 2008)

Wind speeds have also variations during the day. These values are highly site specific and tend to have a lot of random variation that is hard to simulate. (Dai, Deser 1999) This is why daily variations inside the day were derived from statistical data. The majority of wind capacity is located in southern part of the Baltic Sea region in other words Germany and Denmark. That is why variation data was based on hourly wind data from those countries in 2015. Average hourly wind patterns for both summer and winter scenarios were constructed and these multipliers used with all wind production data.

As technologies develop further, capacity factors can change. Possible changes have to be considered with each of the renewable production types in the table 7. Of these production types, hydropower is the most developed. Hydropower has been utilized for hundreds of years and the technologies have been perfected. (IRENA 2012a) No considerable changes in capacity factor for hydropower are expected during the scope of this study, so the capacity factors remain the same in all time periods.

Wind and solar power technologies are a bit less technologically developed. New materials and technological solutions are being developed for both these production types to increase their capacity factor. Wind power is expected to have small improvements in capacity factors during the next few years mainly because of material developments and turbine design. These allow power to be produced at lower and higher wind speeds. According to International Renewable Energy Agency (IRENA) and National Renewable Energy Laboratories (NREL), an increase of 5% in capacity factors is expected. After that the development slows down. (IRENA 2012b) (Chapman et al. 2012). This kind of development was applied to both offshore and onshore wind power capacity factors.

Solar power is the newest and least developed of these production types. This is why bigger increases in capacity factors can be assumed. New technologies exist, and are being developed, that can capture solar energy from lower angles than previously. This can be done by either better absorbing materials and/or altering the angle of the panels according to sunshine. This increases the operation time of the electricity production. As the development is in quite an early phase, an accurate forecast is difficult to make. In this study it is expected that the overall capacity factor value of all solar power production increases near to the level of the highest capacity factors reached today. This means approximately 1 % annual increase in the capacity factor. (Drury et al. 2012) (Fraunhofer ISE 2016)

5.1.4 Pricing of production

European electricity producers use short term marginal costs when pricing their production as explained in chapter 4. This means that price is set based on the cost of producing the electricity which depends on power plant type and the used fuel. These prices are used as a limit which determines if a producer starts to sell electricity or not. This is why determining marginal prices for each production type is required for the market simulations. As with capacity factor, the pricing does not affect all production types.

In this simulation coal, fossil oil, fossil gas and biomass production price their production according to marginal costs. Wind, solar, hydro and nuclear are considered as price inelastic production types. This means that the price of the electricity doesn't affect whether the electricity is produced or not. With solar and wind power this is quite self-evident. With these production types it is not possible to adjust production according to electricity price because the availability of the resource decides the production hours. That is why marginal costs of production are not relevant in this simulation.

The same principle is applied to nuclear and hydro production but for a different reason. Unlike solar and wind, hydropower is relatively easy to dispatch when needed. Only small amounts of production is mandatory to keep the river and reservoir system balanced. Pricing hydropower is complex and it is based on opportunity costs. (IRENA 2012a) However, as can be seen in production merit of order, figure 13 in chapter 4, the marginal cost of hydro power production is lowest of all production types, usually around 4 €/MWh (Norges vassdrags- og energidirektorat 2015). Although the figure is not accurate, it shows that cap in merit order is practically always coal or gas production of electricity. Therefore the market price of electricity is always higher than the marginal cost of hydro power. This means that hydro capacity is used constantly in electricity production and its price won't affect the market price.

Nuclear power is also considered price inelastic. The power plants are slow to turn off and on and the marginal cost is low compared to the other production methods. This means that the capacity is used almost all the time and price won't affect production very much. These price inelastic producers make bids to the day-ahead system that look like the example on the right in table 3 in chapter 4. These kind of bids have only two price steps, the minimum and maximum and same production amounts for both. Marginal costs and their development for price inelastic production types are not considered in this simulation.

The marginal costs for price elastic electricity production are shown in table 8. These values for 2015 are based on the Norwegian Water Resources and Energy Directorate (Norges vassdrags- og energidirektorat) (NVE) report on costs of production. These values were compared against values from EIA, Canada's National Energy board and Open Energy Information platform. As these values were specific for the Nordics and seemed to correlate well with other sources, they were selected as baseline for marginal costs. Future marginal costs were determined in a similar way as previously. Multiple sources were compared and single annual growth rates were selected for each production type.

Table 8: Marginal costs of price elastic production types. (Norges vassdrags- og energidirektorat 2015) (National Energy Board 2016) (Open Energy Information 2015) (EIA 2015b)

	Marginal cost [€/MWh]			
Production type	2015	2020	2030	2050
Coal	29.9	31.2	33.8	39.8
Fossil oil	339.3	388.1	507.6	868.3
Fossil gas	63.1	67.7	77.8	102.7
Biomass and waste	67.0	69.1	73.3	82.5

All marginal costs seem to grow during the next decades. The growth depends a lot on fuel costs but also on price of emissions as these are all CO_2 emitting production methods. The fastest growth of price can be expected from fossil oil production while others grow less dramatically. Biomass and waste production had a lot of variation in costs. Specific fuel and power plant types have big differences in marginal costs and an average value was chosen for this simulation. This was also the case with different kinds of power plant types in all the other production types.

5.1.5 Capacities and connections

To successfully simulate electricity flows between bidding areas the system needs data about existing connections and their transmission capacities. The area configuration, existing and future connections can be seen in figure 16. This map shows PCIs the 17 bidding areas and in addition “areas” NO1A, DK1A and PLA. These are not real areas but line sets which are used to optimize transmission capacities between multiple areas. This means that capacity DK1A-DK1 consists actually of two connections SE3-DK1 and NO2-DK1.

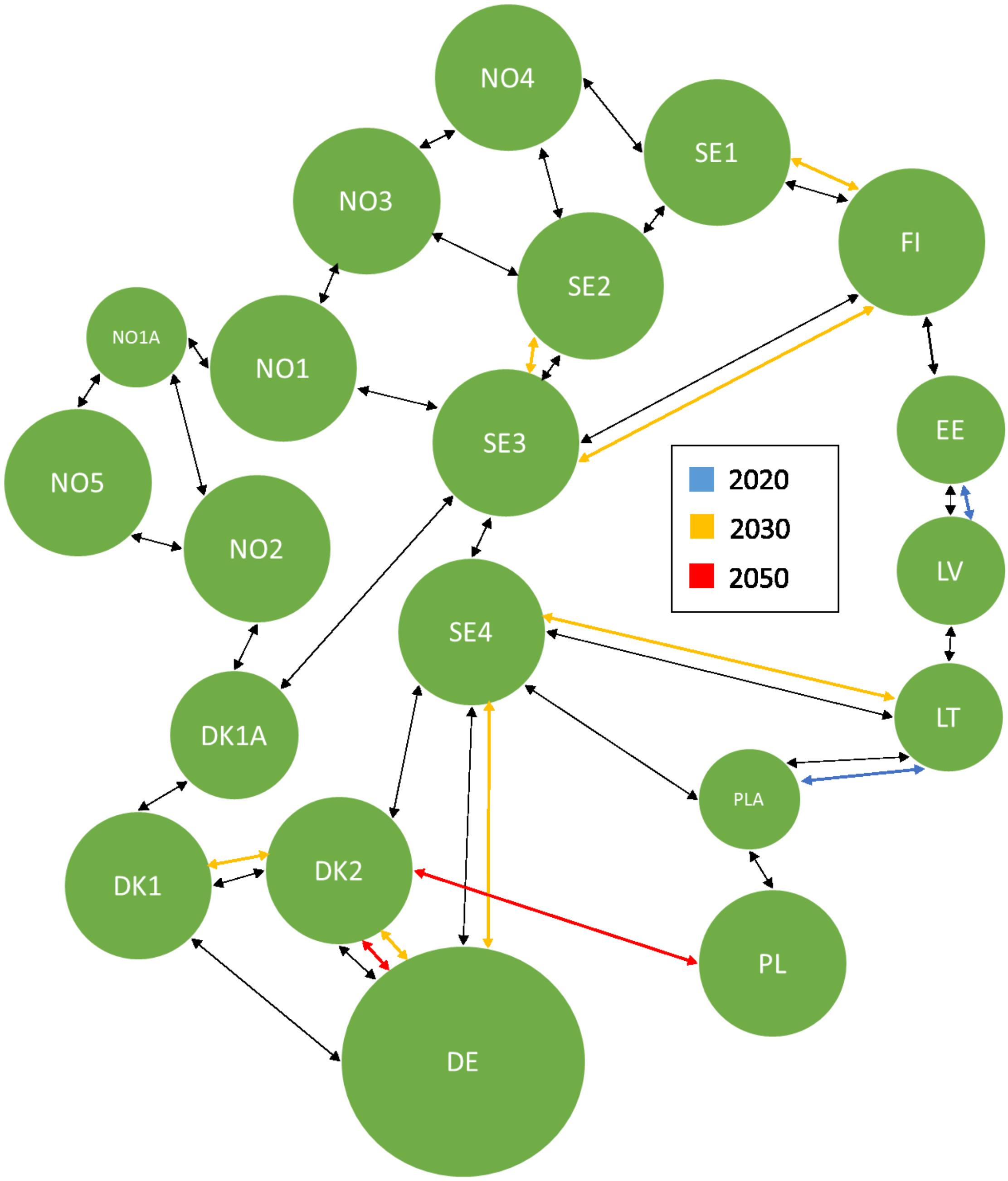


Figure 16: Simplified map of existing and planned transmission lines in Baltic Sea region.

The map shows also both existing and future transmission lines considered in this study. There are actually multiple transmission connections between the bidding areas but in this study the lines are considered as single transmission lines as the total transmission capacity is the only parameter that counts. Inside the bidding areas the transmission capacity is considered infinite. Coloured arrows in the map show the new planned transmission lines for each period of time.

The existing capacities were extracted from Nord Pool data download centre. Available capacities are not always the same because of maintenance and unexpected failures that reduce or cut off the transmission capacities. In this simulation the transmission lines were expected to have full capacities at all times. Planned extension projects of the grid are picked from the list of PCI's. These projects of common interest are listed in the ENTSO-E's TYNDP as explained in chapter two. The planned projects that were included in this study can be seen in table 9.

Table 9: Planned transmission line projects. (ENTSO-E 2015a)

Year	Connection	Name	Capacity increase(MW)
2020	EE-LV	Estonia-Latvia 3rd IC	500
	PL-LT	LitPol Link Stage 2	750
2030	FI -SE1	3rd AC Finland-Sweden north	500/800
	DE-SE4	Hansa PowerBridge 1	700
	LT-SE4	NordBalt phase 2	700
	DK1-DK2	Great Belt II	600
	SE2-SE3	SE North-south reinforcements	700
	DK2-DE	-	600
	FI-SE3	Fenno-Skan 1 renewal	300
	DE-SE4	Hansa PowerBridge 2	700
2050	DK2-DE	Kontek-3	600
	DK2-PL	-	600

The list in table 9 includes the planned transmission lines between the bidding areas. The list of PCI's includes also other projects inside the areas and for example offshore wind grid connections but they are not relevant for this study. Capacity increases are similar to both directions except for FI-SE1 connection which has bigger capacity increase in SE1 to FI direction. Transmission line development plans especially between countries have to be made well in advance as the processes are slow. That is why the list can be considered reliable until the year 2030. The same can't be said for 2050. As seen in the table, only two projects exist to increase capacity in the Baltic Sea area between 2030 and 2050. In reality more connections will be built before 2050 but they are not considered in this simulation. Possible inadequacies in transmission capacities in the 2050 situation will be considered in the results analysis chapter of this study.

5.2 Simulation process

The simulation consisted of total of 11 days which represent the different periods of time in this study. Each of the time periods had prices calculated for both average winter and summer days. To better detect inadequacies and weaknesses in the electricity system, the low renewable scenarios were calculated for the winter days of 2020, 2030 and 2050. Winter days were chosen because the demand is higher and more strain is put on the transmission grid. These were simulated so that solar power production was decreased to zero and wind power production was decreased by 50% while demand remained the same.

The process of simulation in this study works as described in chapter four. Multiple bids were created for both supply and demand side in all the areas. To keep the simulation simple, single demand bids were created to consist all demand in an area for that specific time period. Supply of electricity had to be divided by production type in each area because of the differences in production principles described earlier. For all the production types existing in an area a single bid was created. Capacity factors and market prices were considered and altered to fit all different scenarios in the simulation. Capacities were then inserted to the system with specific values for each year.

Supply and demand bids are converted then to curves by the simulation system. These curves are aggregated to form a single demand and supply curve for each area in the system which gives the total volume of production and demand for each hour of the day. A file is created containing these curves for each area and sent to Euphemia algorithm with a file containing transmission capacities and information on the topology of the network. The algorithm solves the optimization problems using the data and finds the optimal area prices for each area. The Euphemia algorithm also finds the optimal flows of electricity between the areas to balance price differences. The results are saved in the system and extracted from there for closer examination.

6 Results and analysis

This simulation of the Baltic Sea region electricity market was aimed to give better understanding over the effects of the EU energy strategy. The simulation results include three different viewpoints on the development of the electricity market. Flows between the bidding areas will give information on the adequacy of the grid investments and pinpoint possible weaknesses. Generation volumes will tell how the available capacity is utilized and how the production will change over the time period in this study. Area and system prices also received from this simulation. These give direction of the development of the prices in the bidding areas.

6.1 Generation

The simulation calculated the prices for each day that represented a different scenario. These prices determined which bids are accepted and which were not. The data from the accepted bids gives the realized production volumes for each production method in each area. This data was then compared against the actual production capacities and utilization percentages were determined. With the production volumes the figures that represent the hourly production with each production method could be created.

The utilization percentages of different production methods give a lot of information over the electricity market. Example of utilization percentages can be seen in table 10. This table shows values for Finland Hour 12-13 and 00-01 for each scenario. Table shows value 1 if the available capacity is fully used and 0 if none of it is used. In the table we can see that production with biomass and waste is practically zero in all 2015 and 2020 scenarios. Production capacity is put to use only in the winter and in the low renewable scenarios in 2050. Capacity is utilized more in the daytime during highest demand. This is the case in all bidding areas of the simulation.

Table 10: Production utilization in Finland in each scenario, hours 12-13 and 00-01.

12-13	2015S	2015W	2020S	2020W	2020LR	2030S	2030W	2030LR	2050S	2050W	2050LR
Biomass	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.53	0.00	0.36	0.54
Coal	0.62	1.00	0.67	1.00	1.00	0.66	1.00	1.00	1.00	1.00	1.00
Gas	0.00	0.28	0.00	0.38	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Nuclear	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	1.00	0.94	0.99	0.97	-	1.00	1.00	-	1.00	1.00	-
Wind Offshore	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00
Wind Onshore	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
00-01											
Biomass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.14	0.31
Coal	0.34	0.82	0.41	0.90	0.99	0.21	0.89	1.00	0.53	1.00	1.00
Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Nuclear	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	-	-	-	-	-	-	-	-	-	-	-
Wind Offshore	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wind Onshore	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

This lack of utilization is a result of faulty pricing of biomass production in this simulation. As biomass production is used already today in many areas this can't be plausible. In reality part of the coal production would be replaced with biomass production also in the summertime. The majority of biomass is used as a part of the processes in paper and forest industries to produce electricity and heat. In these cases the fuel is gained as a by-product of the process and thus the marginal costs are also lower. In addition both Finland and Sweden with large biomass capacities have feed-in tariffs that support the utilization of this production method. The tariffs diminish the price difference but are not considered in this simulation.

Combined heat and power (CHP) production has also effect on utilization of coal, gas and biomass. A great deal of coal, gas and biomass production in the Baltic Sea area is done using CHP technologies. These powerplants get their profits partly from the heat production and thus in some cases electricity is produced even if the price for electricity alone is not sufficient to cover the costs. This has effect on the electricity production especially in the winter when the need of heat energy is higher.

Coal production on the other hand is in more stable use. It is fully utilized in almost all the scenarios with exceptions in summer 2015 and 2020. The good utilization percentages is partly a result of biomass pricing. High utilization percentages are seen in all bidding areas. However, in Germany, Sweden and Denmark the high renewable capacity in the Germany and Denmark eliminate coal production almost totally in the 2050 scenarios. Another issue with coal production is high variation. Differences between summer and winter and also day and night production is high. In some cases in the 2030 and 2050 scenarios the variation can change from almost zero to full production in a matter of hours.

This is of course not possible for most conventional power plants as increasing and decreasing production can take several hours. This kind of variation is better responded using gas or oil production. Differences between summer and winter are also quite notable. The low production utilization in the summer would mean that for great deal of the year the power plant wouldn't be economically feasible. This would mean that a part of the production capacity would be decommissioned.

Both gas and oil utilization is very low. This is a result of unrestricted elasticity of the coal production. In table 10 the gas production is used only at daytime and mainly in winter and low renewable scenarios. Similar figures are also seen in other areas. Gas utilization is highest in the areas of Norway in the winter and in the low renewable scenarios with almost full utilization. In other areas, a reasonable, above 50% utilization can be detected in the high demand situations during the daily peaks in winter and low renewable scenarios.

Oil utilization is lowest in this simulation. This is because it has the highest market cost of all production methods. Oil production is put to use only in the 2050 low renewable scenario in Poland. Both gas and oil utilization percentages are lowered due to flexible coal production. In reality these two would be used to respond to variations created by renewable production and coal would mainly be used as a base load. The pattern of production, with majority of production during the peak hours, is still visible at least with the gas production and the oil production would follow that.

Nuclear and hydro production are used as a base load in all scenarios. As nuclear production is not flexible and both hydro and nuclear power are so cheap they are both used all the time during this simulation. No variation can be seen in either of these production types as seen in table 10. Exception to this is nuclear capacity in Sweden and Germany in the 2050 simulations. Germany's renewable production is so high that nuclear production has to be decreased slightly in order to prevent excess production. This cheap renewable electricity is transmitted to Sweden where it has the same effect only less dramatic. This is visible in both summer and winter scenarios. In reality nuclear capacity would not be decreased but renewable electricity would not be fed in to the grid. Also Germany has plans to decommission its nuclear capacity by 2022 but this was not considered in this study.

Cheap wind production both on and offshore are used in a similar way as the nuclear and hydro production. Because of their cheap pricing they are used almost whenever they are available. In these scenarios wind is expected to blow in all scenarios rather steadily so good production volumes are expected. Utilization is close to full in almost all areas again with an exception of Denmark and Germany. The 2050 scenario has great variations due to the large solar capacity and this affects also wind production. The wind production is decreased up to 40 % in some cases during the summer 2050 scenario.

Solar production is as well utilized nearly fully whenever it is available. Great variations can be detected with this method because the production pattern follows the amount of solar irradiation. As seen in table 10 the solar power is not in use during the nights but fully utilized in the daytime. This creates a lot of variation in the system and forces other production types to adjust their production accordingly. This creates instabilities in the 2030 and the 2050 scenarios.

Figure 17 with combined production patterns from the 2020 and 2050 scenarios shows the utilization of production types and development of the production volumes more clearly. The left side figures are 2020 and right side 2050 production patterns. First two represent the summer scenario, second two are from the winter and last two from the low renewable scenarios. The first thing to notice is the scale of the figures the peaks of production volume are almost 60 GW higher in the 2050 scenarios compared to 2020 scenarios. This is why the height of the areas shouldn't be compared but the actual values.

Great changes in production volumes between the 2020 and 2050 scenarios can be detected. Most dramatic changes are related to renewable production volumes as table 6 in chapter 5 with annual growth rates of production methods suggests. Peak solar production volume for summer is more than doubled in the 2050 scenario compared to 2020. The winter scenario shows even more dramatic change. Wind production values, especially offshore, are also rapidly increasing. Small offshore wind volumes grow from being almost trivial in 2020 to one of the biggest in 2050.

Differences between the summer, winter and low renewable scenarios are easily detected from these pictures by looking at the solar production volumes shown with the dark blue color in the figures. The summer scenarios have notably more solar production volume than the others. In the 2050 winter scenario the solar volume is still rather high as the technologies are expected to improve during the monitoring period. In the low renewable scenarios the solar volume drops to zero. In these scenarios the wind production is also dropped to half of winter scenario's value.

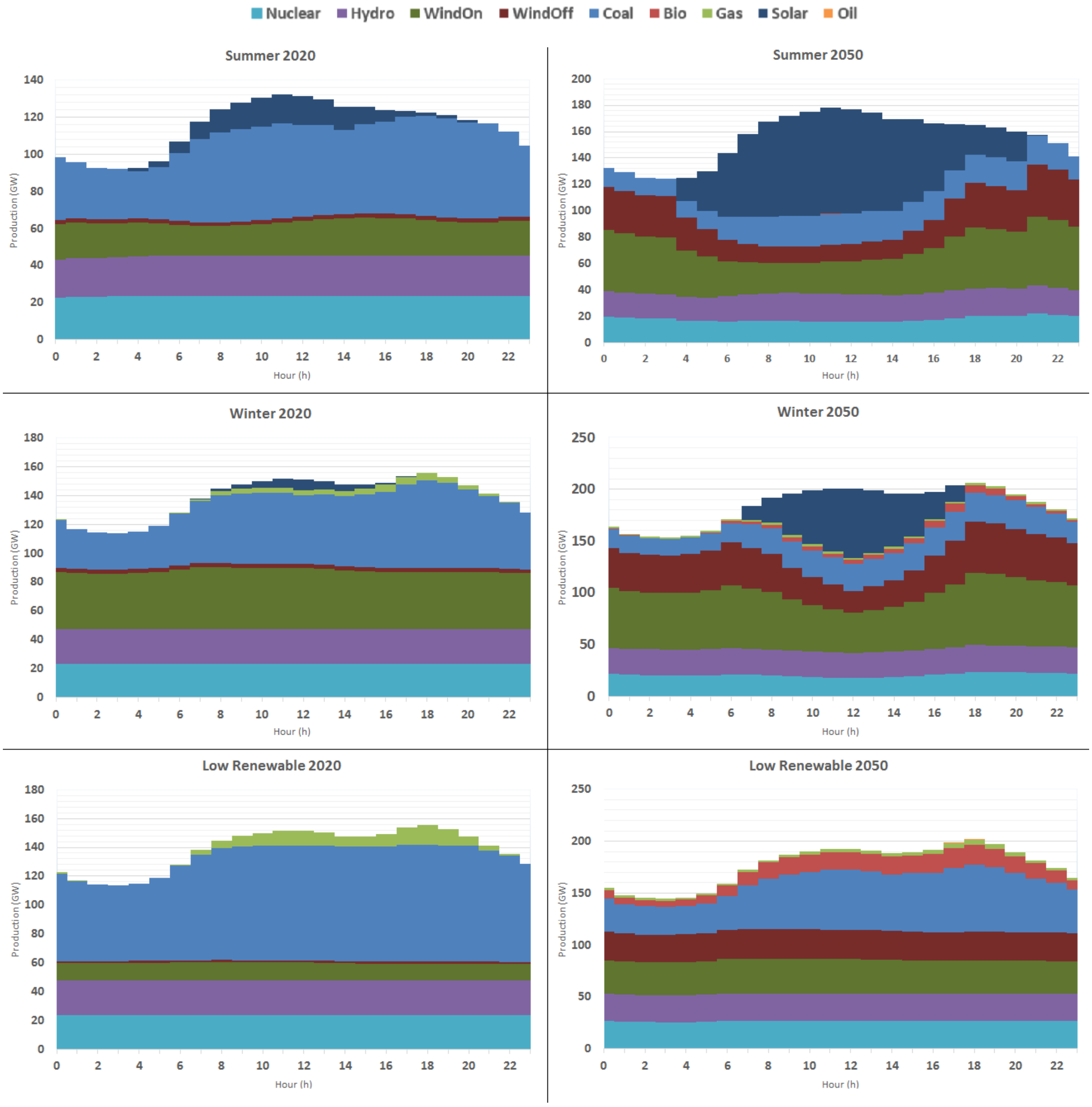


Figure 17: Production pattern comparison between 2020 (left) and 2050 (right) scenarios in the Baltic Sea area.

The deficit of power in winter and low renewable scenarios replaced in 2020 scenarios mainly using gas production. Cheaper biomass production is not used as the areas with deficit have no biomass capacity and the transmission lines are congested so the required capacity can't be transmitted. In the 2050 scenarios the deficit is larger as renewables create more seasonal variation. In these scenarios the majority of deficit is replaced with biomass production. Gas production is also used in addition with small amounts of oil production not visible in the figures.

The issues regarding the 2050 scenarios can be seen clearly in these figures. During summer scenario the daily variation with solar production is between zero and 70 GWh and back to zero in 12 hours. This creates challenges to other production types such as coal production which is required to allow rapid changes in production volumes. These issues are most visible in the areas with big renewable capacities such as Germany. More flexible production capacity is needed to handle these variations.

Flexibility is also needed in low renewable scenarios. The figure 17 shows that in the 2020 scenarios low renewable day doesn't differ that much from regular winter day. This is also the case with the baseline scenarios. Nearing 2030 and especially 2050 the solar and wind production volumes for a regular winter days increase so much that low renewable day produces great variations to the system. Variations of nearly 90 GWh are possible in the 2050 scenario. These variations may be very rapid as both solar and wind conditions may change a lot even during the day.

6.2 Prices

Utilization of different production methods affects also the prices as the most expensive production method used sets the price for all production. From the results of this simulation both system and area prices could be extracted. As explained before, the area prices take into account restrictions in the transmission capacity between the areas while the system price ignores them totally. System price is calculated purely based on the demand and production bid curves.

In this study the system price is used to define the overall development of the prices in the Baltic Sea region. Comparison between the different scenarios can then easily be made because flows between areas are not taken into account and the price is same throughout the simulated system. Area prices are used to present some special situations that occur in certain bidding areas exclusively.

In the figure 18 the hourly values for system prices in each situation are presented. The curves in the figure seem to increase or decrease in steps. This doesn't represent the real situation but is the result of equal pricing for all production units of certain production type. In reality the curves would change more gradually. Differences in prices between winter and summer scenarios are clearly visible when comparing for example 2015 and 2020 winter and summer scenarios.

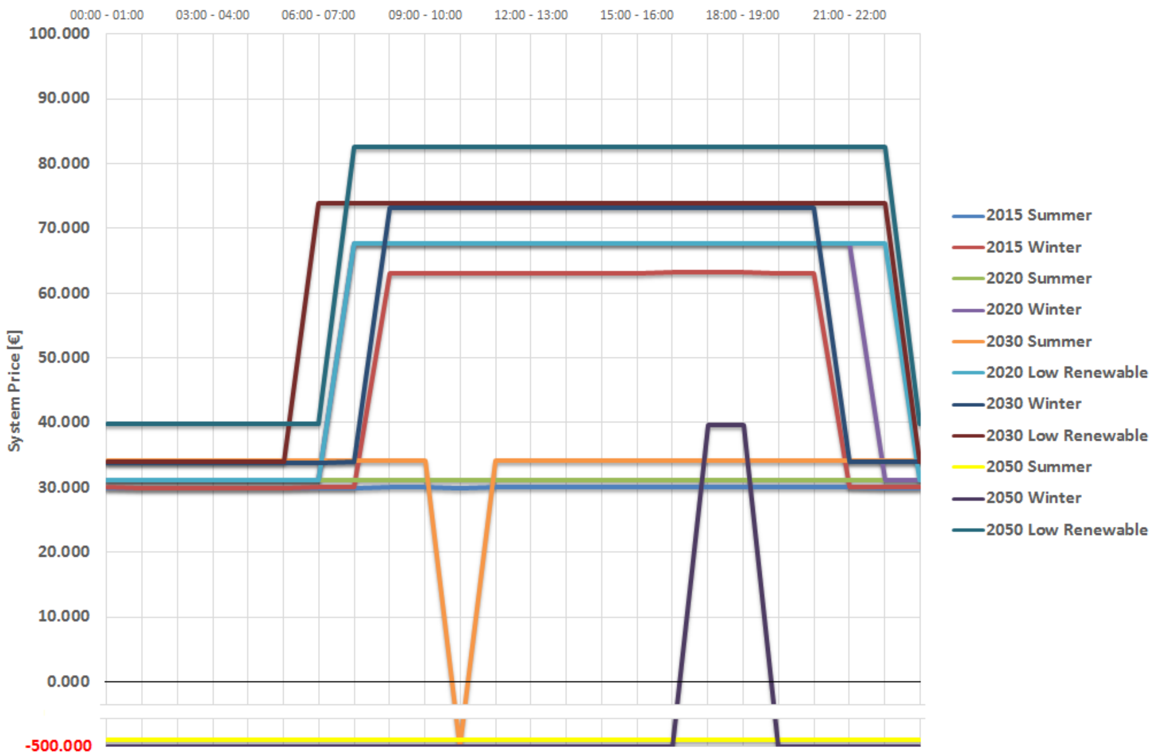


Figure 18: Hourly system price values in the Baltic Sea area in different scenarios.

While both summer days have flat system price curves near 30 €/MWh, the price of coal production, winter days make a step up to 63 €/MWh in 2015 and 68 €/MWh in 2020 scenario. This is due to increased demand of electricity in the peak-load hours and need to start electricity production with gas. The prices around 60 represent the price of electricity produced with gas-fired power plants. The increase of marginal costs from 2015 to 2020 explain the price difference between the scenarios. While the low renewable scenario curve follows closely the winter curve in 2020, it differs from the winter scenario by having longer high price duration.

The curve for summer 2030 is rather different from the corresponding 2015 and 2020 curves. It too has a steady level of about 34 €/MWh, representing the marginal cost of coal production but it also has a minimum price situation in hour 10:00-11:00. A negative price of -500 €/MWh is reached for that hour only. After this, the price level rises back to its normal level. This is a result high renewable production capacities which push the prices down. There is an excess of production and as the pricing of renewables is inelastic in relation to prices, the system price plunges down. Rising demand pushes the prices back up after the minimum price hour.

The winter and the low renewable scenarios for 2030 seem to follow the same pattern as 2015 and 2030 curves. In both these situations the biomass production is taken into use but as price development has made gas production more expensive than biomass, it still sets the price, this time to a level of 74 €/MWh. In these scenarios too the prices in the low renewable scenario stay at this higher level longer than in normal winter day. This is due to the smaller availability of cheap renewable production capacity.

Looking at the 2050 curves the prices change dramatically. Excess of production, resulted by increase of non-dispatchable production capacity, reduces the prices. Many areas with lots of variable renewable capacity and their neighbors, such as Germany, Denmark and Sweden face negative prices. For the summer 2050 scenario the prices are at their minimum the whole day. In the winter scenario the solar and wind production are still so high that the system price stays at the minimum level throughout the day. Only during two hours when the demand is still high but solar capacity is decreasing the prices increase to coal production’s price level at 36€/MWh. The low renewable scenario on the other hand is similar to the corresponding curves for other time periods, lower prices in the morning rising to a higher level during the day and decreasing to the original level in the evening.

System price tells a lot about the overall status of the electricity system: the power production methods, possible excesses in production and pattern of demand. As it ignores capacity restrictions between the countries, some aspects about the condition of the system can’t be detected using only system price. That is why the area prices should also be investigated to form a more detailed picture. As the production, demand and connections to other countries are different in bidding areas, so are the area prices. In the next paragraphs area prices from three different areas are examined.

6.2.1 Finland

The area prices in this scenario in Finland represent situation in the Baltics and Sweden and Norway in most cases. The area prices in Finland for all scenarios can be seen in figure 19. Prices for the summer are on a relatively stable level following the growth of coal marginal price throughout the years. When it comes to 2050 the differences begin. In Finland there are two price peaks that occur at peak load situations. In the Baltic area the situation is similar but in Sweden and Norway cheap renewable power from Germany pushes prices to negative.

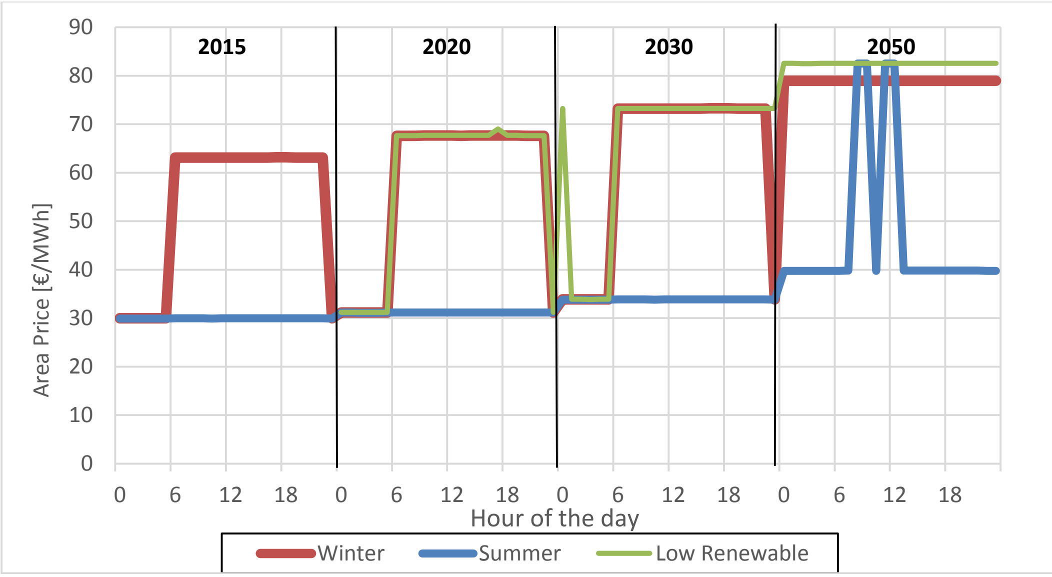


Figure 19: Development of the daily area prices in Finland during the investigation perdiod in Winter Summer and Low Renewable scenarios.

In the winter the prices rise to a higher level during the high demand hours due to gas or biomass production utilization. The low renewable scenario is similar to normal winter scenario. As Finland has very wide portfolio of production types, reducing renewables does not have very much effect on the prices.

6.2.2 Poland

The vast majority of Poland's power production is coal-fired as can be seen in figure 14 in chapter 4. This reflects clearly on the area prices in figure 20. In all scenarios until the 2050, the prices stay at the coal marginal price level. Poland's coal production capacity is enough to fulfil the demand along with exported electricity.

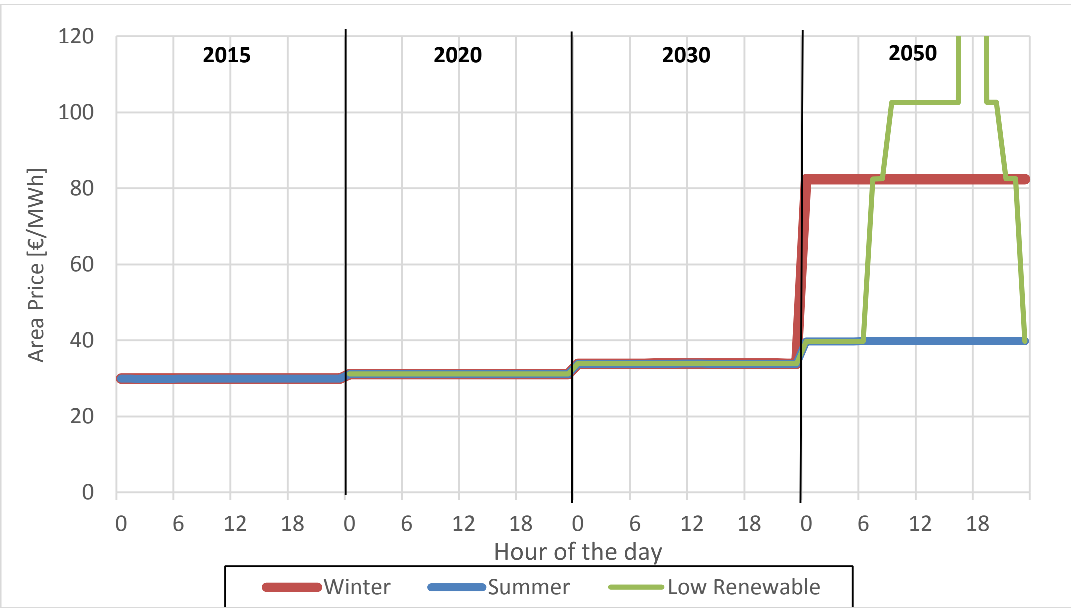


Figure 20: Development of the daily area prices in Poland during the investigation perdiod in Winter Summer and Low Renewable scenarios.

Change to that comes in the 2050 scenarios. While the summer scenario follows in the path of previous years, winter and especially low renewable scenarios change. In the winter the prices are higher as demand is higher and the coal production is not anymore sufficient. Production using biomass needs to be started. In the low renewable scenario the prices first step up to biomass production price and then further up to level of gas production price of 102 €/MWh. During the day also oil production must be started to meet the demand and prices rise to even higher level to around 800 €/MWh. After that the prices fall back to original level as demand decreases towards the midnight.

6.2.3 Germany

The area price of Germany in figure 21 represents the situation in areas with large shares of variable renewables. This means in the Baltic Sea region both the areas of Germany and Denmark. The summer and winter curves are similar to the situation in Poland up to year 2030. After this the great share of renewables in production causes variability in prices. However as the renewable production from solar power is decreased in the winter, the price stays at a stable level also in the winter 2030 scenario. In the summer scenario the prices drop to minimum due to excess in production during the high solar production hours. As the amount of renewable capacity is increased the prices for both winter and summer fall to -500 €/MWh during the 2050 scenario.

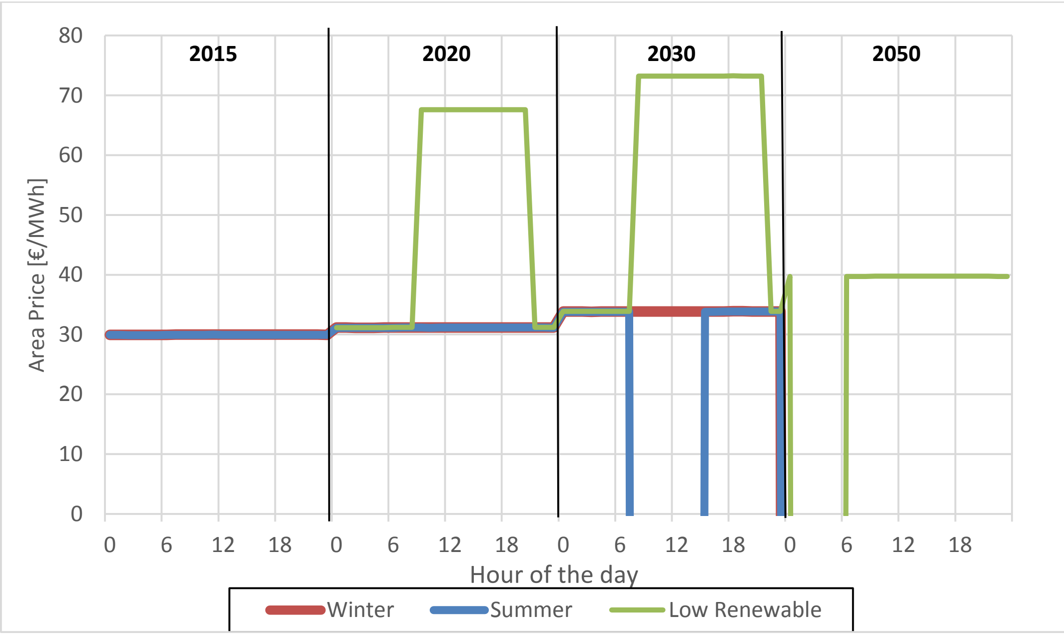


Figure 21: Development of the daily area prices in Germany during the investigation perdiod in Winter Summer and Low Renewable scenarios.

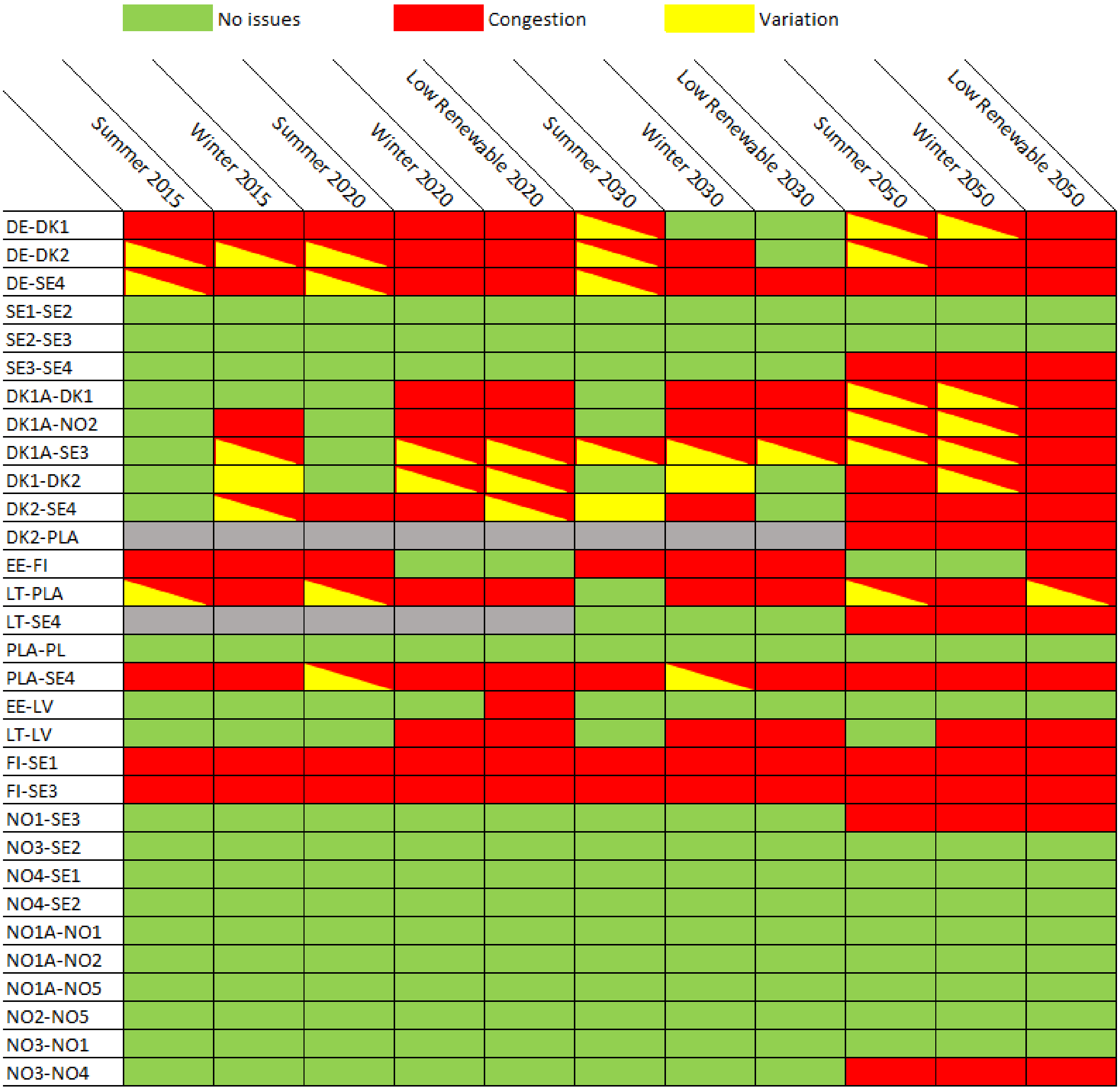
The large renewable production capacity causes negative prices in the areas when production levels are high. In the low renewable scenarios the price curve is similar to corresponding scenarios in Finland. As the demand rises biomass and gas production must be started as solar, wind and coal production are not enough to meet demand. The year 2050 makes exception to this. As the renewable production capacity, mainly wind in the low renewable scenario, is on so high level that even in the low renewable scenario the prices are at minimum during the lowest demand hours.

The system price and individual area prices differ from each other quite dramatically. This is why it is important to investigate both. As Germany has the largest volumes in production and demand the system price curves are closest to situation in Germany. By detecting area specific price patterns more detailed picture of the situation can be achieved.

6.3 Electricity flows

A perfectly working transmission grid could direct the power flows optimally from areas with lower prices to areas with higher prices and provide equal prices in all areas. As could be seen in figures 19, 20 and 21 this is not the case in Baltic Sea region. Variating area price levels can be detected already in the 2015 scenarios. By investigating the electricity flows between the areas and comparing those against available capacities, congested parts of the grid could be located. To avoid unnecessary complexity the connections between areas were grouped to seven different groups. The connection groups are Baltic internal, Sweden internal, Norway internal, Nordic internal, Continental-Nordic and Baltic-Nordic. Major issues regarding electricity flows between the countries are documented in table 11 below.

Table 11: Issues in transmission lines between countries in each scenario.



There are two kinds of issues shown in the table that cause problems in electricity grids. First and more often occurring is the congestion, which means lack of transmission capacity between the areas. This causes differences in the prices as the cheaper electricity can’t be transmitted without restriction to an area with higher prices. Variations mean variations in flows and direction of flows. Situations in which the flow in the transmission line is 200 MW in hour 1 to one direction and 500 MW in hour 2 to the opposite direction may cause strain to grid infrastructure. This is why ramping or change in the power flow is restricted in many transmission lines. However, to successfully finish price calculations, these restrictions needed to be removed in this simulation.

The Baltic internal connection group consists of connections between the Baltic countries Estonia, Latvia and Lithuania and in addition Poland. In the summer scenario the flows inside the Baltics go from north to south i.e. from Estonia to Latvia and Latvia to Lithuania. In the winter and low renewable scenarios the flow is in the opposite direction. The same is occurring also in the 2020 scenarios. Neither of the previous time periods face notable congestion in the transmission lines. The connection from Poland to Lithuania differs from these as it has flow towards Lithuania in all scenarios. This transmission line is congested especially in the summer.

The completion of new transmission lines in 2030 and 2050 seems to change the direction of the flows. In these scenarios the summer flows from north to south are turning towards south to north direction. More power is flowing to Lithuania which is transferred in this direction. Congestions are occurring in both transmission lines in 2030 winter and in all 2050 scenarios.

Sweden and Norway are both divided into multiple bidding areas. The connection groups Sweden and Norway internal seem to handle the changes little better than the Baltics. Both these connection groups seem to be able to handle the development of the grid quite well at least until 2030. After that the scenarios show that some congestion is present in the peak demand hours in SE3-SE4 and NO5-NO2 connections. Also rapid changes in the directions of the flow can be detected in these connections. As large capacities of solar power is put to use in Germany the directions of the flows can change rapidly.

Between the Nordic countries the situation is variable. Between Sweden and Norway the situation is similar to Sweden and Norway internal connection groups. These connections handle the development well until the year 2030. After that some minor congestions are observed especially in the southest connections. Between Finland and Sweden the situation is different. The flows are in all scenarios from Sweden to Finland and the lines are almost always congested.

Denmark is a transfer area of electricity between Germany and the other Nordics. That is why connections from Denmark to other Nordics act in a similar way as connections from Germany to its northern neighbors. This is why they are described together. The situation in the connection group Continental-Nordic is the most complex. As the production patterns change the most in this region the changes are also most dramatic. In summer 2015 the direction of the flows are from Nordics to Denmark and Germany. The biggest, almost congesting flows are occurring during the first and last five hours of the day. During the peak load hours in the middle of the day the flows are lower. In the winter the flows are almost at maximum in the opposite direction from Germany and Denmark to Nordics.

The flows in 2020 scenarios are quite similar to 2015 situation. The difference is the increase of variation in flow amounts in the summer scenario. In the middle of the day the flows are near zero while they keep on being at full capacity during the first and last hours of the day. The winter scenario keeps having some congestion in flows from South to North. The low renewable scenario in 2020 is quite similar to the winter scenario but the congestion in the transmission lines last longer.

Nearing the 2050 scenarios the flows keep changing. In the 2030 scenarios the summer pattern is similar to previous cases. Difference is that now the variations are even larger. While early mornings and late evenings have congestions towards Germany, now during the day congestions are appearing to opposite direction as well. The winter flows are running now at maximum capacity to North. The low renewable scenario shows still congested flows to Sweden and Norway. Flows from Germany to Denmark are slightly decreased due to the increase in Denmark's own renewable production.

The 2050 scenarios seem to follow this development. In summer the variations are getting even more sudden. In the winter and low renewable scenarios the flows from Denmark turn towards Germany to provide replacement for low solar production. From Germany to other Nordics the flows keep on being at their maximum level.

Four connections exist between the Baltics and Nordics as Poland is considered as a part of the Baltics in analyzing the flows. Transmission line from Denmark area 2 to Poland is completed in 2050. This connection is really needed as the transmission capacity is fully used to transmit electricity to Lithuania in all scenarios. The connection between Finland and Estonia is used also almost exclusively to provide electricity to Baltics. This line is especially congested in the summer scenarios.

Connection between SE4 and Lithuania is also congested, especially in the 2050 scenarios. The flow is in all scenarios towards the Baltics. The fourth connection between SE4 and Poland faces increasing congestions as the years progress. The 2015 scenario has only few congested hours in the middle of the day but in 2050 the congestion lasts for the majority of the day. Big variations can also be detected between morning and day hours.

The table 11 shows all the congestions and variations that may be problematic in the future are displayed. Congestion problems due to increasing production can be detected in most of the transmission lines especially in the southern and eastern part of the region. Significant variations which are caused by the increase in variable renewable production capacity are located in the southern part of the region.

6.4 Summary

As the simulation results pointed out, several challenges are facing the Baltic Sea electricity market in the following decades if the described scenarios become reality. Changes are mostly a result of significant reform of the regions production mix. While nuclear and hydropower remain as baseload providers, both offshore and onshore wind increase to match their capacities. In addition to wind power, solar production increases rapidly as well. Total production volumes with variable renewables increase considerably as can be seen in figure 17.

As the simulations show, this may result to a situation with excess production in the summer. In the winter or especially when the variable renewable production is low the risk of power shortages increases as the share of renewables grow. (Hiroux, Saguan 2010) Unlike in this simulation, in reality conventional coal-fired power plants are not able to keep up with the rapid changes resulting from variations in renewable production. New more flexible production capacity is needed to handle this variation.

Another problem facing the producers of electricity in a system with large amounts of variable renewable production is the seasonal variation. Lower or even zero utilization percentages in the summer during good renewable production conditions cause problems to producers without renewable capacity. Cheap and ample variable renewable electricity makes the production with conventional methods unprofitable during several months. This will result in decommissioning of power plants and further increases the risk of shortages.

As prices are determined by the most expensive production method in use, the rapid increase of practically zero marginal cost production pushes the prices down. In this simulation the area prices varied a lot depending on the production mix and connections to others. In the areas with large amounts of variable renewable production the area prices tended receive negative values. The same issue was observed in the areas connected to these high renewable production areas.

Negative prices can be really harmful for the producers as they actually have to pay the buyers for receiving their electricity. This is presently not an issue, as negative prices occur very seldom. In the future this seems to occur reasonably often according to simulation results. Negative prices wouldn't however last for very long as power plants would be shut down quickly if the cost paid to customers would exceeded the cost of shutting and starting the production. This would in any case further harm the producers that provide important capacity during low renewable scenarios. (EPEX 2016)

Negative prices are usually an indicator of insufficient transmission capacity. The area prices are not negative throughout the Baltic Sea region even in the 2050 scenarios. This means that the excess electricity could be spread more efficiently to areas with higher prices to at least reduce the durations of negative price periods. Congestions in the transmission lines are an increasing issue as the time passes towards 2050. This is partly because in this simulation the 2050 scenario doesn't include all transmission projects that are going to be finished by the year 2050.

Clear indication in where the grid improvements should be concentrated are clearly visible in the table 11. The Nordics and Continental Europe needs a lot more transmission capacity between then to be able to handle the increasing amount of solar production in Germany. Also new technologies are required to make the grid more flexible against variations in power flows. Baltics and Finland should also be better connected to the other Nordic countries and Continental Europe to better spread the excess electricity production.

7 Conclusions

The implementation of the EU energy strategies is progressing well. The far reaching plans to integrate and liberalize heavily segmented European electricity markets to a single pan-European electricity market has taken significant leaps forward. The liberalization process that dates back to 1990s took the first steps to increase competition and make the markets more efficient. The Energy packages lead the way to more ambitious and comprehensive plans that were targeted to revolutionize the whole energy sector of the European Union.

Having common energy policies requires common decision making. To steer the development of the European energy sector and to form common policies, Energy Union was formed. Its goals are to provide the EU citizens with sustainable, secure and competitive energy. By joining forces in decision making the European Union could stand up to other big players in the global energy sector. Better optimization of resources is possible by having a single entity to control the development inside the whole EU. The implementation of even more ambitious plans in an efficient manner is considerably easier when the control is centralized.

The Energy 2020 plans set the scope of EUs energy policies to include the whole energy sector with more environmentally conscious angle. The ambitious plans were supposed to cut emissions, improve efficiency and increase the share of renewables by 20% by the year 2020 in all member states. Even if some member states are falling behind, most of these plans are still within reach at EU level as explained in chapter 2 of this study. The EU 2020 targets were set on national level which might be considered problematic as some member states were already almost reached the target levels when the plans were introduced while others were still miles away. This might have discouraged the endeavors to really push for the targets as reaching them was going to require insuperable efforts.

This is probably why the 2030 and 2050 plans are much more considerate towards national characteristics. These more far reaching plans have discarded more or less the targets of energy efficiency and renewable share. The emission reduction targets are the only ones still binding the member states in these plans. The point in this is that in order to reach the emission reduction targets, energy efficiency must be improved and renewable share must be increased. This is more suitable way of setting targets in a community this big and diverse. It is up to member states to decide the methods of reaching their individual targets.

Still the same methods keep on appearing in some form in almost all of the EUs energy policies. Increasing the share of renewables is considered the most important method in cutting emissions. Replacing the power production with coal using renewables is the method of choice in many EU countries. Research and development efforts are also directed towards new and more efficient equipment. Efficiency could be improved almost everywhere starting from household appliances and better housing to transportation and industrial equipment.

The EUs energy plans have also identified the electricity grids to be in a key position in enabling these changes. Replacing large amounts of steady and dispatchable power production capacity with variable and unpredictable renewable production is very risky without efficient transmission grid. The poorly interconnector or totally isolated areas face constant risk of power cut-offs due to power plant failures or other disturbance. Isolation hinders also competition in the area which may lead to unfair pricing. Creating a single pan-European electricity market would bring security of supply, cheaper prices and enable integration of more renewable capacity. Failing or succeeding in creating the single energy market can alone define the outcome of the EU energy plans. This is why the development of the electricity grids has been a priority in the EU policies from the beginning.

The plans for EUs energy market in 2020 include targets for interconnection rate. Each member state is required to increase the transmission capacity to neighboring countries to 10% of the total production capacity by 2020. A further target also exists that proposes this figure to be increased to 15% by 2030. A lot of countries have already more than 15% interconnection rates in 2015 as seen in table 2 in chapter 3, but is this enough to handle the dramatic changes in the following decades.

Liberalization of the markets is also a key in creating the single European electricity market. Today the Europe is divided to several market regions in which a single power market operates. Allowing free competition in the markets and breaking the final barriers between these regions is vital for the EU plans to succeed. Though a lot of progress has been made in transforming from national markets to current state, the single European electricity market is still an ongoing process.

A lot of ambitious plans are steering the development of the European energy sector for many decades to come. These plans also include well defined methods of reaching these targets, but are they enough to revolutionize the energy system. This study aims to investigate the impacts of these plans in the Baltic Sea region and pinpoint the issues that might be faced in the future while implementing the energy strategies.

The conducted simulations indicate that either the plans are too ambitious or the methods of reaching them are not adequate. There are several PCIs that are supposed to support the upcoming changes in the energy markets and help in building the single electricity market. Even if the 2050 scenario surely lacks multiple projects that are not yet even being planned, problems can be identified also in the earlier scenarios. Several connections between the countries have congestions even in the 2015 scenarios as seen in table 11 in chapter 6. Problems are especially between continental Europe and the Nordics where the congestions and also rapid variations in power flows are present in multiple cases. The lack of interconnection capacity is increasingly greater in the later scenarios as hours that have maximum flows in the transmission lines are increasing.

The 2030 and 2050 scenarios have both considerable amounts of variable renewable production. This is clearly visible in the figure 17 in chapter 6. This is of course great for reaching the emission reduction targets, but in the transmission grid it causes problems. The rapid variations in power flows originating from huge solar capacity in Germany cannot be handled with current grid infrastructure. As well as improvements in technology, huge increases in capacity are also needed in order to cheap solar electricity to flow unrestricted to all parts of the region. In the simulations the situation is clearly not optimal. The huge differences in the area prices indicate that the grid is not efficient enough to distribute the electricity evenly.

The issues won't stop there if the amount of variable renewables is increased to such levels as the EU plans indicate. The marginal costs of solar and wind power production are so low that other production methods are unable to match them. As seen in the simulation results negative price situations are expected to dramatically increase in the future as seen in figure 18 in chapter 6. Even today negative prices occur, but in the future it will become more of a habit than a rare phenomenon. Having negative prices is of course harmful for the producers of electricity and will drive the producers of electricity to decommission production units.

The prices of fuels and burning them will most likely increase in the future due to the EU emission trading system and other policies. This will make the production of electricity with conventional methods even more unprofitable. Due to this, massive amounts of production capacity will be decommissioned in the future. Low electricity prices also hinder investments in the energy productions and no replace capacity would be built.

A situation in which the electricity is produced mainly using the variable renewable production is very risky in regard of supply security. The simulations didn't take into account the decommissioning of the power plants and this is why there were no cut-offs of power in any area. Most of the power plants that in the simulations kept the demand satisfied in the low renewable situations would in reality be decommissioned. In situations in which the production levels of solar and wind go down rapidly the risk of power outages or restrictions in demand are very likely at least in the 2030 and 2050 scenarios.

Of course there are methods with which these problems could be alleviated. Electricity storaging and demand flexibility introduced in chapter 3 are both possibly methods actively used at least in the 2050 scenario. These two and various other technologies still in development could change the energy sector totally and make the implementation of these plans much more fluent. These technologies are unfortunately still mostly in research and testing phase and little commercial use exists. Massive investments to these technologies have to be made in order for them to become the saviors of the EU energy plans. As pointed out before in this study, future of these technologies is impossible to predict that far in future. However, it would be highly inconsiderate to rely only on the possibly upcoming technologies while implementing the strategies.

Other methods need to be considered in order to keep in track with the present good progress in implementing the EU energy strategies. More resources are needed to improve the transmission grid and political efforts made to create the single electricity market. This is the absolute key to successful implementation of the energy strategies. Transmission technologies have to be improved and existing ones utilized more frequently in order to allow more renewables to the grid in a controlled manner. The grid should also be planned not regionally but as a whole to support the future integration of the markets. This will ensure equal prices, supply security and sustainably throughout the system.

If the grid improvement and market integration should fail, other means need to be considered to create the path for the future. Great shares of renewables in the electricity system do not combine well with poorly functioning transmission grid. If the grid is not able to handle the change, the renewable capacity must be controlled. Denying access to grid for renewable producers is of course not a desirable outcome but might be necessary if the grid improvements fail. Other possibility is having a large capacity of rapidly dispatchable production to balance the system in varying production situations. This would most probably mean large increase in gas or oil fired production as they usually are relatively fast to dispatch. For these backup producers different pricing methods needs to be designed as for most of the time the plants are not used and paying for electricity only makes them unprofitable.

In spite of all the problems that might be faced in the future, ambitious plans are required to make a difference. Aiming high in the strategies, pushes the European Union to strive for better energy solutions. The future plans that may sound very far reaching create a mind-set that promotes efforts to develop new even more effective technologies that could make these plans a reality. However, the restrictions and facts must not be forgotten while planning the future of the European energy system.

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